SOLAR STILLS: PERFORMANCE AND ECONOMICS

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SOLAR STILLS: PERFORMANCE AND ECONOMICS

BY

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THESIS

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN ENGINEERING

THE UNIVERSITY OF TEXAS AT AUSTIN

August 1982

to my parents and grandmother

Viktor, Mira and Matilda

ABSTRACT

Performance and economic analysis of shallow basin type solar stills is given in this work. A simple FORTRAN program for transient performance of solar stills (SOLST) has been developed based on the physical model developed in chapter two. This program, together with a solar still economics model (chapter four), can be used for evaluation of a variety of proposed or existing solar still plants. A simple example is presented (chapter five), which shows that changes in certain design parameters (insulation and side wall thickness) affect the overall performance and cost effectiveness of solar stills. That is, for given meteorologic and economic circumstances, there is an optimal still design which will provide fresh water at the minimum cost.

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NOMENCLATURE

A_c - Area of still cover (m^2)

AP - Annual payment (%)

A_s - Side wall area (m^2)

A_w - Brine surface area (m^2)

C_c - Heat capacity of cover ($J/K\text{-}m^2$)

C_{in} - Heat capacity of finite insulation element ($J/K\text{-}m^2$)

C_s - Heat capacity of finite soil element ($J/K\text{-}m^2$)

C_w - Heat capacity of brine ($J/K\text{-}m^2$)

D - Fraction of direct insolation (-)

d_{in} - Insulation thickness (m)

d_s - Side wall thickness (m)

$F_{0-\lambda}$ - Blackbody radiation fraction (-)

F_{w-c} - Shape factor from water to cover (-)

h_c - Convective heat transfer coefficient from the cover to environment ($W/m^2\text{-}K$)

h_{cv} - Convective heat transfer coefficient from brine surface to cover ($W/m^2\text{-}K$)

h_{fg} - Latent heat of vaporization (J/kg)

h_s - Side wall heat loss coefficient ($W/m^2\text{-}K$)

$\dot{H}_{w,i}$ - Enthalpy rate of incoming brine (W/m^2)

$\dot{H}_{w,o}$ - Enthalpy rate of outcoming water (W/m^2)

I - Global hourly insolation on horizontal surface (W/m^2)

I - Capital investment of a still plant per m^2 ($\$/m^2$)

$I_{a,c}$ - Solar energy absorbed in cover (W/m^2)

$I_{a,w}$ - Solar energy absorbed in brine (W/m^2)

I_{DIF} - Diffuse component of insolation (W/m^2)

I_{DIR} - Direct component of insolation (W/m^2)

I_0 - Capital investment of standard still ($\$/m^2$)

$I_{r,c}$ - Solar energy reflected from cover (W/m^2)

$I_{t,c}$ - Solar energy transmitted through cover (W/m^2)

k - Extinction coefficient of cover (m^{-1})

k_{in} - Conductance of insulation material (W/m-K)

k_s - Conductance of soil (W/m-K)

k_{sid} - Conductance of side wall material (W/m-K)

L - Cover thickness (m)

L - Specific lenth of still (m)

L - Required labor for supervision (h/year)

$\dot{m}$ - Distillate output rate ($kg/s\text{-}m^2$)

MR - Maintenance and repair (%)

N - Day of the year (-)

n - Index of refraction of cover (-)

n - Payout period (years)

Nu - Nusselt number (-)

P_c - Vapor pressure of water at T_c (Pa)

P_w - Vapor pressure of water at T_w (Pa)

Q_B - Base heat flow (W/m^2)

Q_{CV} - Convection from brine to cover (W/m^2)

$Q_{CV,C}$ - Convection from cover to atmosphere (W/m^2)

Q_E - Evaporation from brine to cover (W/m^2)

Q_L - Leakage of water vapor (W/m^2)

Q_R - Radiation from brine to cover (W/m^2)

$Q_{R,C}$ - Radiation from cover to sky (W/m^2)

$Q_{R,out}$ - IR radiation from brine through cover to sky (W/m^2)

Q_S - Side heat loss (W/m^2)

$Q_{S,C}$ - Conduction through side walls (W/m^2)

Q_T - Global daily insolation on horizontal surface (MJ)

r - Interest rate (%)

Ra - Rayleigh number (-)

rII - Parallel component of unpolarized radiation (-)

$r\perp$ - Perpendicular component of unpolarized radiation (-)

S - Cost of raw materials ($\$/m^3$)

t - Time (s; h)

T_a - Ambient temperature (K)

T_c - Cover temperature (K)

TI - Taxes and insurance (%)

T(j) - Transient soil temperatures (K)

$T_{in}(j)$ - Transient insulation temperatures (K)

T_{max} - Maximum ambient temperature (K)

T_{min} - Minimum ambient temperature (K)

T_s - Terminal soil temperature (K)

t_s - Daylenth (h)

T_{sky} - Effective sky temperature (K)

$T_{s,o}$ - Outside wall temperature (K)

T_w - Brine temperature (K)

V - Cloud intermittency (-)

V_w - Wind velocity (m/s)

Y - Ground depth at which is T_s constant (m)

Y_D - Yearly distillate output (l/year)

Y_R - Yearly rainfall collection (l/year)

α - Absorptance of cover (-)

α_{in} - Thermal diffusivity of insulation (m^2/s)

α_s - Thermal diffusivity of soil (m^2/s)

δ - Solar declination (^{o})

ΔF - Factor from radiation tables (-)

$\Delta \dot{H}$ - Enthalpy rate change (W/m^2)

ΔI - Incremental investment ($\$/m^2$)

ΔT - Equivalent temperature difference between water and cover (K)

ε_c - Cover emittance in IR (-)

ε_w - Water and basin liner emittance in IR (-)

θ - Angle of incident radiation on cover (R)

θ_2 - Angle of refraction in cover (R)

θ_e - Effective angle of incidence of diffuse insolation (R)

λ - Wavelenth (m)

λ - Geographic latitude (^{o})

ω - Hour angle (R)

ρ - Reflectance of cover (-)

σ - Stefan Boltzman constant ($5.72 \cdot 10^{-8}$ W/m^2-K^4)

τ_a - Transmittance where only absorption losses are considered (-)

τ_{IR} - IR transmittance for plastic cover (-)

τ_r - Transmittance where only reflection losses are considered (-)

τ_λ - Wavelenth dependent transmittance (-)

1. INTRODUCTION

Solar distillation is a process for getting fresh water from sea water using the sun as the source of energy. The first mention of solar distillation appeared as early as the 16th century in Italy and France.

Although the basic principles involved in a distillation process were well understood earlier, the first distillation plant was built in 1872. It was erected in Las Salinas, Chile, had 4800 square meters of collecting area and was constructed by a Swedish engineer, Mr. Charles Wilson. The plant, shown in the photograph of figure 1, provided drinking water for over 40 years, and has been mentioned in almost every article dealing with solar distillation.

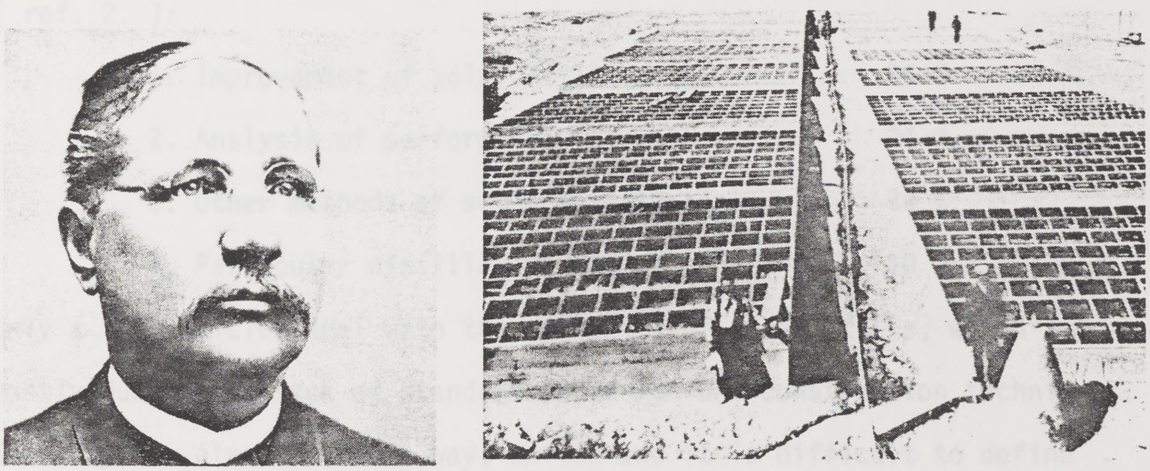

Figure 1. Mr. Charles Wilson and his solar distillation plant built in 1872 in Las Salinas, Chile. Photo courtesy of Dr. Telkes.

In the first half of 20^{th} century there was little interest in solar distilation and only a few people were involved in research. Between World War II and the early seventies, many institutions began investigating different aspects of solar distillation. Table 1-I shows some of the institutions and investigators in this period. An excellent compilation of all the research and experimental work, together with a listing of all solar distillation plants built around the world is given in ref. 1.

The thermal behavior of solar stills is quite well understood and there is a considerable amount of experimental data from existing stills. A significant number of investigations are presently underway in many countries. The published articles dealing with solar distillation during the period 1978 - 1981 can be devided roughly into four groups (ref. 2.):

1. Improvement of solar stills	36 %
2. Analysis of performance	34 %
3. Other methods of solar distillation	20 %
4. Particular distillation projects	10 %

Only a few articles deal with the economics of solar stills, which is mostly due to the lack of standarized design and construction techniques. So every new plant is, in a way, unique and it is difficult to define standardized cost estimation procedures.

Table 1 - I. Activities on solar stills during period of 1940 to 1970.

From Talbert at al. (ref. 1.).

Investigator
Massachusetts Institute of Technology, New York University, etc. (Telkes)
Virgin Islands (Rounds, Löf)
University of California (Howe, Tleimat, et al.)
University of Wisconsin (Daniels, Duffie)
Battelle Memorial Institute (Bloemer, Eibling, Löf, et al.)
Löf, George
Australia, CSIRO (Morse, Read, et al.)
Algeria (Gomella, Savornin, Lejeune)
Italy (Nebbia)
Bjorksten Laboratories (Lappala)
South Africa, CSIR (P. W. D.-Pretoria, Cillie, Whillier, Odendaal)
Cyprus (Fitzmaurice)
Kenya (Blake, Ramsay)
Chile (Hirschmann)
USSR (Baum, Brdlik, et al.)
France (Trombe, Foex, Gomella)
Senegal, West Africa (Masson)
India (Khanna, Mathur, Datta, Garg, Ahmed, et al.)
Iran (DeJong)
Georgia Institute of Technology (Grune, et al.)
Spain (Blanco, Fontan, Barasoain)
Franklin Institute (Erb)
Morocco (Ambroggi)
Sunwater Company (McCracken)
Egypt, National Research Center (Hafez, Sakr)
Hummel, Richard
University of Arizona (Hodges)
Hay, Harold
McGill University (Lawand, Selcuk, et al.)
Taiwan (Wang)
Japan (Kobayashi)
Tunisia (A.E.C.)
Leslie Salt Company
Aqua-Sol, Inc. (Eckstrom)
Greece (Church World Service, Delyannis)
Cape Verde Islands (Eckstrom)
Ethiopia, Haile Selassie I University (Hobbs)
U.S. Water Conservation Laboratory (Jackson)
Pakistan (A.E.C.)
Solar Sunstill, Inc. (Delano, Raseman)

The current work is an attempt to provide an economic model capable of optimizing still design. At the same time, the intention of this work is multifold:

- To provide an accurate, yet simple, computer simulation program of solar still performance
- To give a better insight in to the economics of solar stills (which has not been treated extensively in the past)
- To propose standard solar still designs for easier comparison with new designs
- To show how different design parameters (bottom, sides) can affect solar still economics

In the following chapters a complete performance model is explained in detail, followed by construction techniques and an economics model. Only the simple basin type solar still geometries (see figures in chapter 3.) are considered here, since they are the only ones, at the present time, that are able to provide drinking water at competetive prices.

2. PERFORMANCE

This chapter will describe the thermal behavior of solar stills and define all the heat fluxes and temperatures in the still. The equations derived will be used for computer simulation of transient solar still performance.

2 - 1 Energy Balance

Figure 2-1-1 shows the energy paths in an operating still.

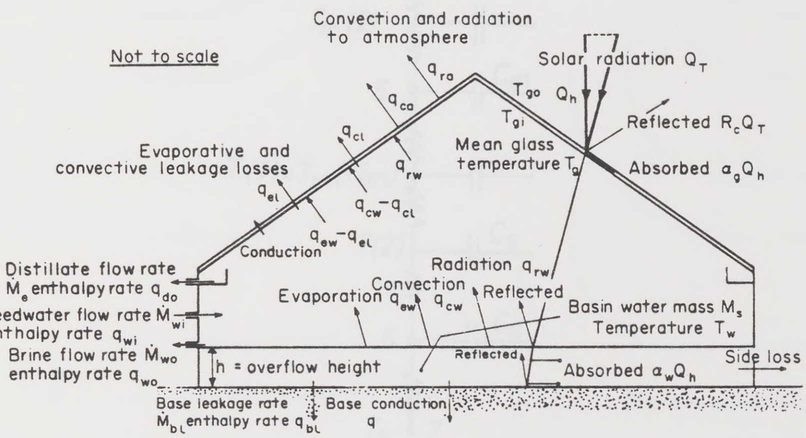

Figure 2-1-1. Solar still heat and mass transfer paths (from ref. 3).

While the still operates in a transient state, some storage terms can be neglected because they are very small compared to the others. This assumption is usually good for the cover and sides, because of their small heat capacity. However, the saline water and the soil beneath the still have large thermal capacity and must be treated in a transient analysis. So the basic thermal network is shown on figure 2-1-2.

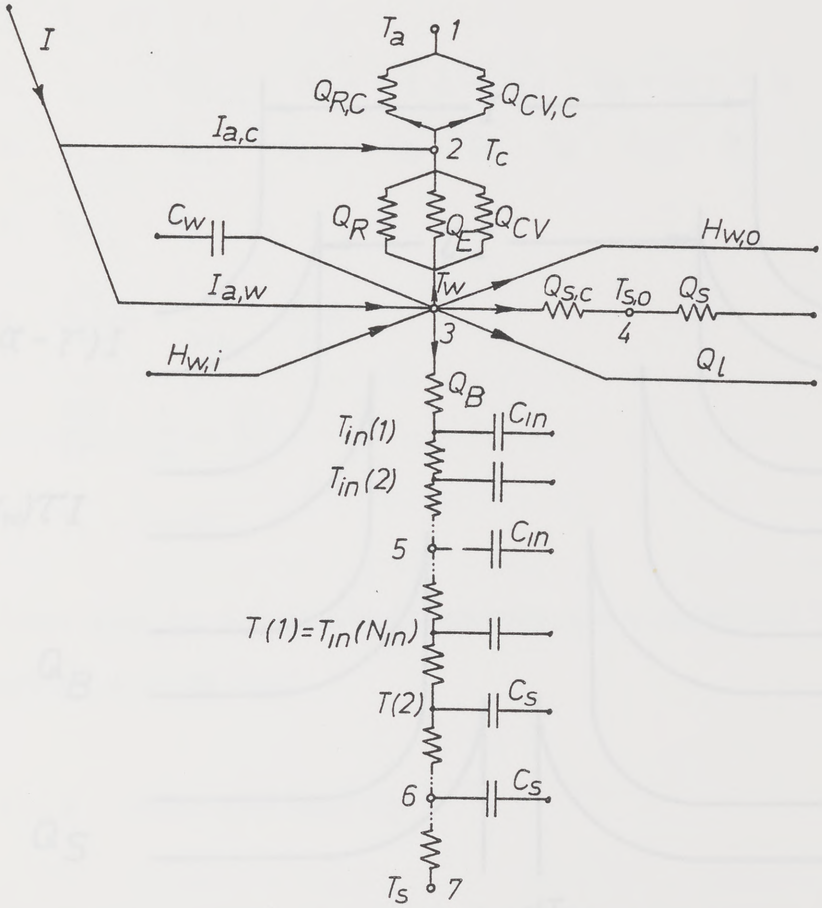

Figure 2-1-2. Solar still thermal network.

The energy flows for the still are shown on figure 2-1-3.

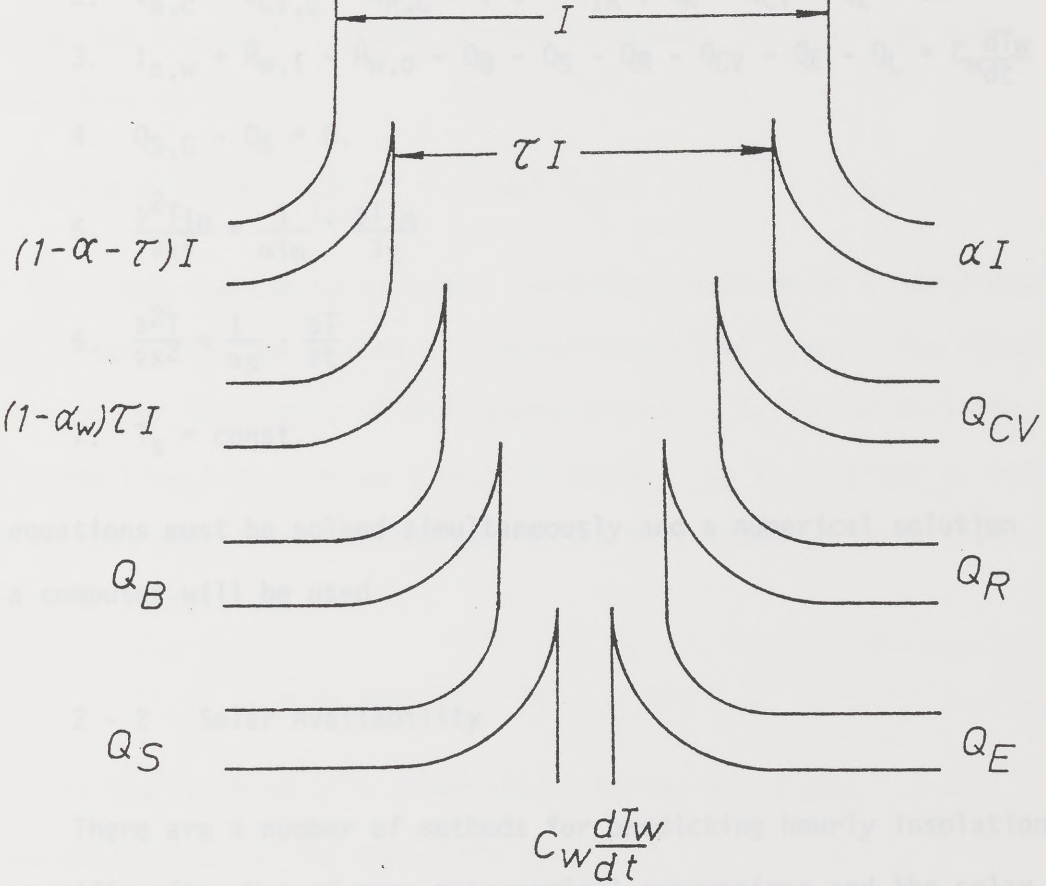

Figure 2-1-3. Heat flow distribution in solar still.

The governing energy balance equations and the boundary conditions can be written for each node on figure 2-1-2.

1. $T_a = f\ (\ t\ )$
2. $I_{a,c} - Q_{CV,C} - Q_{R,C} + (\ 1 - \tau_{IR}\ ) \cdot Q_R + Q_{CV} + Q_E = 0.$
3. $I_{a,w} + \dot{H}_{w,i} - \dot{H}_{w,o} - Q_B - Q_S - Q_R - Q_{CV} - Q_E - Q_L = C_w \frac{dT_w}{dt}$
4. $Q_{S,C} - Q_S = 0.$
5. $\frac{\partial^2 T_{in}}{\partial x^2} = \frac{1}{\alpha_{in}} \cdot \frac{\partial T_{in}}{\partial t}$
6. $\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha_S} \cdot \frac{\partial T}{\partial t}$
7. $T_S = \text{const.}$

These equations must be solved simultaneously and a numerical solution using a computer will be used.

2 - 2 Solar Availability

There are a number of methods for predicting hourly insolation for a specific site. Use of pure astronomical expressions and the solar constant frequently leads to a large inaccuracy. Therefore, it is preferable to use local meteorological data. While hourly insolation data are seldom available, global daily insolation data on horizontal surfaces are available for numerous locations. If not available for a specific location, it can be readily measured on site, interpolated between the nearest stations or read from insolation maps. Interpolation may introduce possible errors because of unique weather conditions at a specific site. On site measurements are preferred, but long term (several years) measurements are needed to provide reliable data for design purposes.

It is frequently assumed that solar radiation on a horizontal surface varies sinusoidally from sunrise to sunset, the relation being (adapted from ref. 3):

$$I = 436.3 \frac{Q_T}{t_S} \sin\left(\frac{\pi t}{t_S} \right) \left(1 + \cos\left(\frac{\pi V t}{t_S} \right) \right) \qquad 2\text{-}2\text{-}1$$

Where: Q_T is the average daily global radiation received on a horizontal surface, V simulates the effect of intermittent cloud cover (the bigger the V the bigger the number of stationary clouds), t_S is the daylenth, and t is the time from sunrise (both in hours). Q_T is obtained by one of the methods mentioned earlier, and t_S can be calculated using the astronomical expression:

$$t_S = \frac{2}{15} \arccos(- \tan \lambda \cdot \tan \delta)$$

Where: λ is the latitude of a given site (North: + ; South: -) and δ is the declination of the sun given by:

$$\delta \cong 23.45 \cdot \sin\left(360. \frac{284 + N}{365} \right)$$

Where: N is the day of the year.

It is actually better to take the daylenght t_S to be somewhat shorter than the time between sunrise and sunset to account for early morning and late afternoon solar attenuation in the atmosphere. A good approximation suggested by Cooper (ref. 3) is one hour. That is:

$$t_S = t_S - 1$$

For intermittent cloud cover, equation 2-2-1 will give radiation distribution as shown on figure 2-2-1.

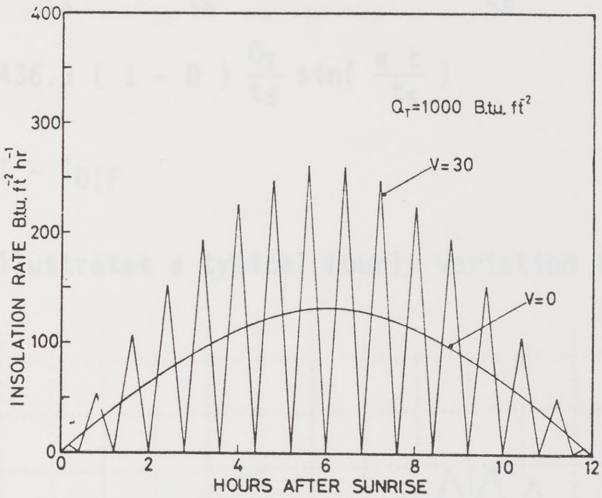

Figure 2-2-1. Insolation profile for intermittency function using equation 2-2-1. (from ref. 5).

Normally, insolation never drops to zero during daytime so equation 2-2-1 is used in a modified form. First, hourly insolation I is split into the direct and diffuse components:

$$I = I_{DIR} + I_{DIF}$$

$$I_{DIR} = D \cdot I$$

$$I_{DIF} = (1 - D) \cdot I$$

Where: D is the fraction of global insolation that is direct on a particular day ($\sim$0.92 for a totally clear day and a dry climate; and 0.0 for a totally overcast day).

It is assumed that D stays constant throught the day and therefore, the diffuse component (I_{DIF}) also varies sinusoidally from sunrise to sunset.

So the hourly insolation distribution used in this work is given by:

$$I = 436.3 \frac{Q_T}{t_s} \sin\left(\frac{\pi t}{t_s} \right) \left(1 + D \cdot \cos\frac{V \pi t}{t_s} \right) \qquad 2\text{-}2\text{-}2$$

$$I_{DIF} = 436.3 \left(1 - D \right) \frac{Q_T}{t_s} \sin\left(\frac{\pi t}{t_s} \right) \qquad 2\text{-}2\text{-}3$$

$$I_{DIR} = I - I_{DIF} \qquad 2\text{-}2\text{-}4$$

Figure 2-2-2 illustrates a typical hourly variation in global insolation.

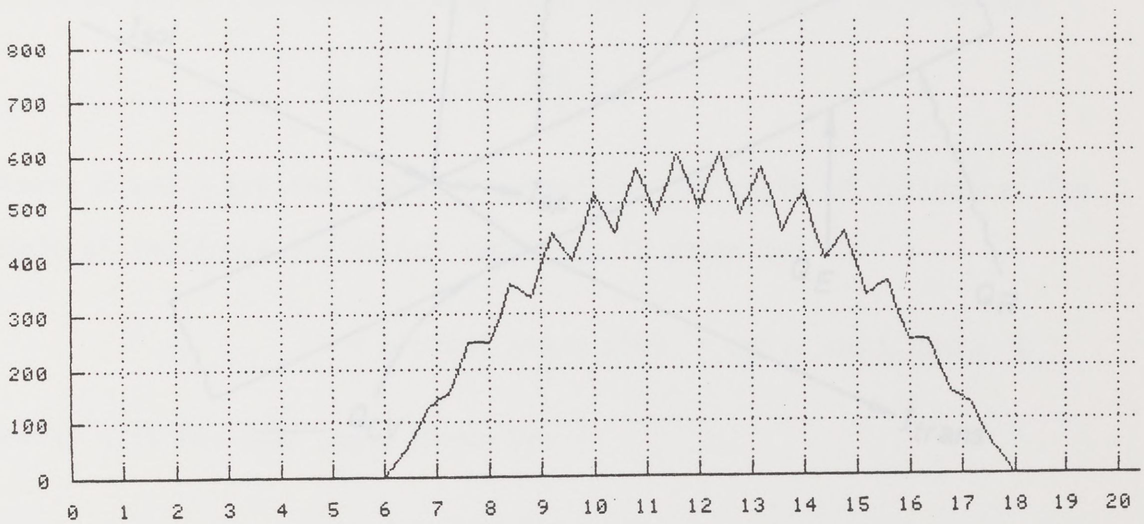

Figure 2-2-2. Global hourly insolation calculated by equation 2-2-2.

2 - 3 Energy Balance on the Cover

There are usually two types of covers used in solar stills: glass and plastic film, each having its specific features. Glass is generally more durable and more expensive, while plastic film deteriorates within one to three years but, is cheaper and easier to install. In addition, it is not unusual that plastic films must be mechanically treated to insure their wettability.

In operation, glass and plastic film behave differently regarding the transmission of radiation.

a. Glass Covers

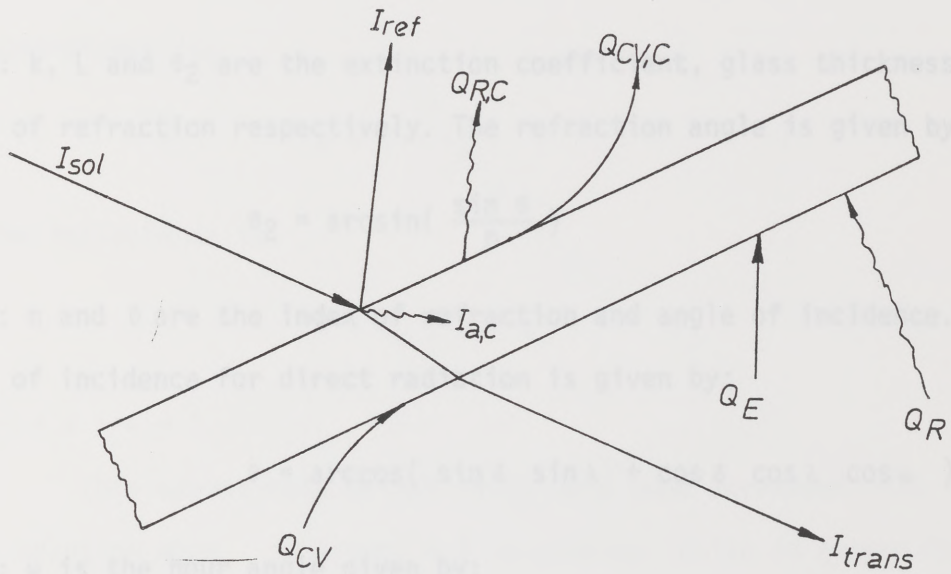

Figure 2-3-1. Energy balance on a glass cover.

Glass reflects a small fraction of radiation and also absorbs a small fraction of the incident solar energy due to its extinction coefficient and its physical thickness. The largest part is transmitted since glass has high transmissivity at the short wavelenghts where most of the solar radiation occurs. Glass is quite opaque to wavelenghts longer than approximately 5 microns.

Although direct and diffuse components of incident radiation obey the same laws of reflection and refraction, they are treated separately herein because of their different angles of incidence. Equations for transmittance, absorptance and reflectance of direct solar radiation for glass are given below. The transmittance resulting from absorption only is:

$$\tau_a = e^{-k\,L\,/\,\cos\theta_2}$$

Where: k, L and θ_2 are the extinction coefficient, glass thickness and angle of refraction respectively. The refraction angle is given by:

$$\theta_2 = \arcsin\left(\frac{\sin\theta}{n} \right)$$

Where: n and θ are the index of refraction and angle of incidence. The angle of incidence for direct radiation is given by:

$$\theta = \arccos(\sin\delta \ \sin\lambda + \cos\delta \ \cos\lambda \ \cos\omega)$$

Where: ω is the hour angle given by:

$$\omega = (t - 12) / 3.82$$

and t is the local time (24 hour time).

The transmissivity due to reflection only is given by:

$$\tau_r = \frac{1}{2} \left(\frac{1 - rII}{1 + rII} + \frac{1 - r\perp}{1 + r\perp} \right)$$

Where the parallel component of unpolarized radiation, rII, is given by:

$$rII = \frac{\tan^2(\theta_2 - \theta)}{\tan^2(\theta_2 + \theta)}$$

and the perpendicular component of unpolarized radiation, $r\perp$, is:

$$r\perp = \frac{\sin^2(\theta 2 - \theta)}{\sin^2(\theta 2 + \theta)}$$

The overall transmittance of glass which accounts for absorption and reflection losses is given approximately by:

$$\tau \cong \tau_a \tau_r$$

The absorptance is:

$$\alpha = 1 - \tau_a$$

and the reflectance is:

$$\delta = \tau_a (1 - \tau_r)$$

since $\tau + \alpha + \delta = 1$.

This approximate method is in very good agreement with the exact solution when is around 0.9 or greater, which is generally the case.

The diffuse component of sunlight undergoes the same process of reflection, absorption and transmission. The only difference is that for diffuse radiation the angles of incidence span the entire hemisphere and the angular distribution is generally not well known. Assuming the incident energy to be independent of angle, Brandemuehl and Beckman (ref. 4) integrated the beam transmittance over all angles and defined the effective angle of incidence for diffuse radiation (i.e. the equivalent angle for direct radiation that gives the same transmittance as for diffuse radiation). Their results are presented on fig. 2-3-2 as a function of the tilt angle, β, of the receiving surface.

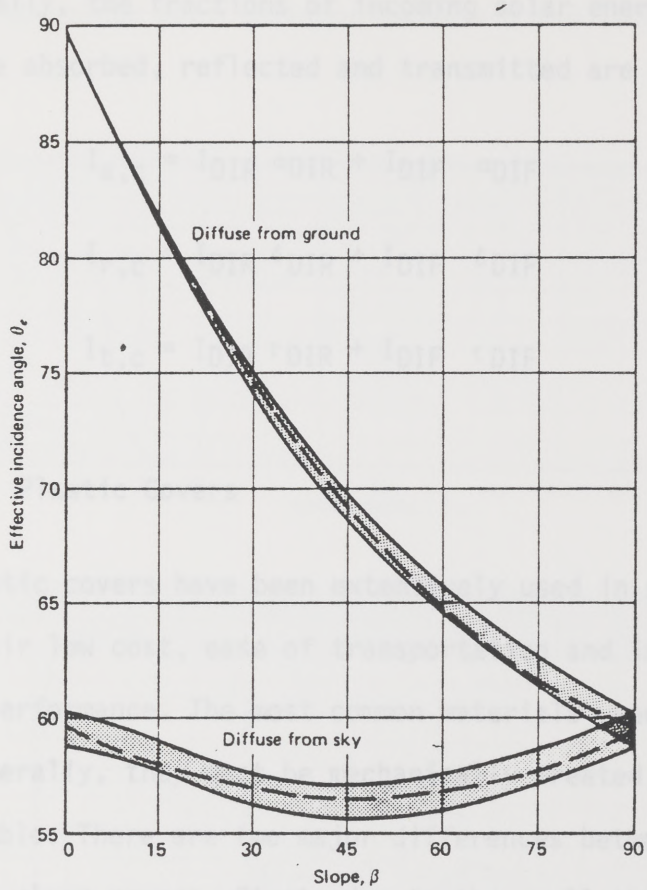

Figure 2-3-2. Effective incidence angle of diffuse solar radiation. From ref. 4.

For the purpose of solar stills, where the cover slope is typically 10^{o} to 15^{o}, the diffuse radiation from the ground can be neglected and diffuse radiation from the sky has an effective incidence angle around 58^{o}.

The transmittance, reflectance and absorptance for the diffuse component of incident sunlight are found in the same manner as for the direct component, except that the incidence angle stays 58^{o} throughout the day.

Finally, the fractions of incoming solar energy on the cover glass that are absorbed, reflected and transmitted are respectively:

$$I_{a,c} = I_{DIR}\,\alpha_{DIR} + I_{DIF}\,\alpha_{DIF}$$

$$I_{r,c} = I_{DIR}\,\delta_{DIR} + I_{DIF}\,\delta_{DIF}$$

$$I_{t,c} = I_{DIR}\,\tau_{DIR} + I_{DIF}\,\tau_{DIF}$$

b. Plastic Covers

Plastic covers have been extensively used in solar stills because of their low cost, ease of transportation and installation and satisfactory performance. The most common materials used are Tedlar and Mylar, and generally, they must be mechanically treated to make their surfaces wettable. There are two major differences between the performance of plastic and glass covers. First, due to the small thickness solar energy absorbed in a plastic cover is practically zero and the temperature drop across the film is negligible. The second difference is due to the optical properties of the plastic materials. While glass is practically opaque for infrared radiation beyond 5 microns, most of the plastic materials are not, as shown on figure 2-3-3. Consequently, in the plastic covered solar stills, a portion of the radiation emitted from the brine is transmitted through the cover and lost. This fraction of radiation from the brine that escapes directly to the sky, can be readily estimated using the radiation tables (for the particular brine temperature, typically 40^{o} C) and transmittance curves (fig. 2-3-3) for any particular plastic material.

All the other heat transfer terms are the same as for the glass cover.

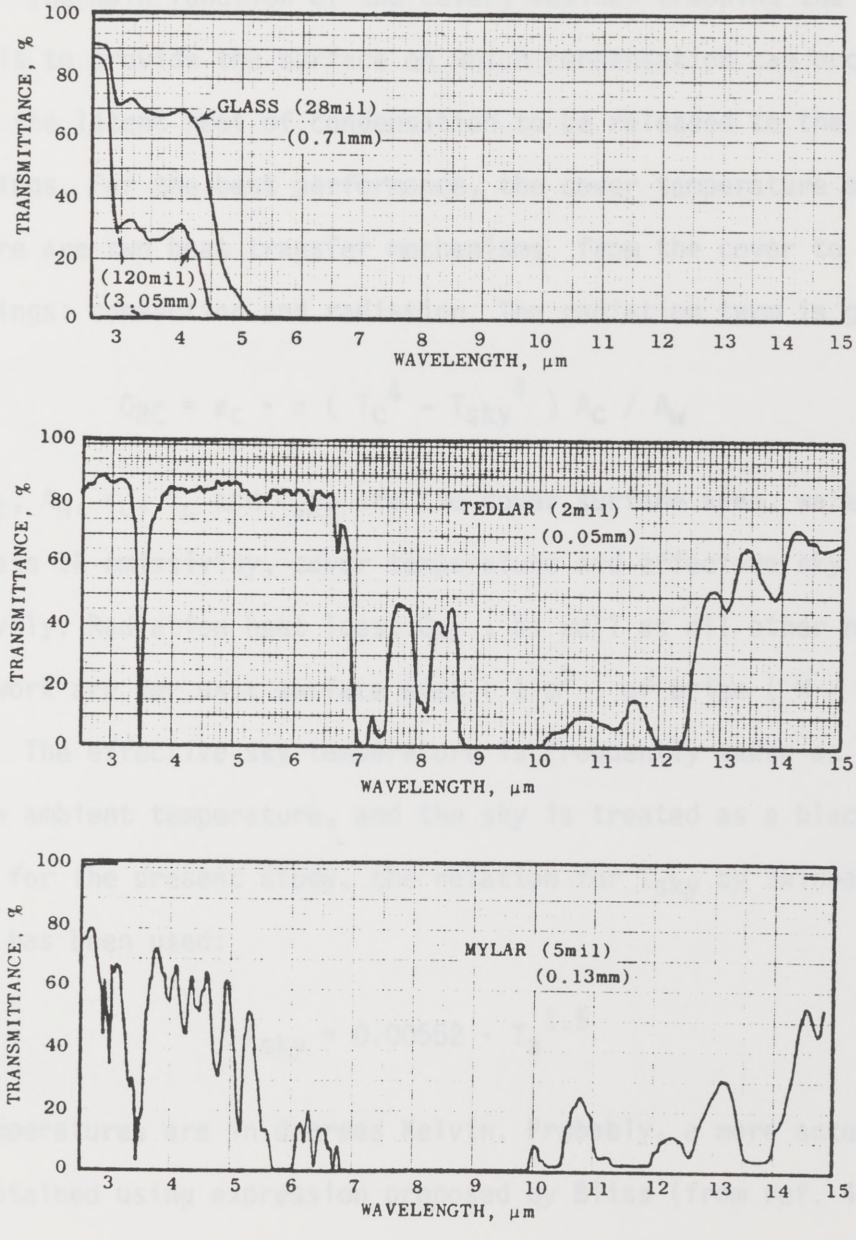

Figure 2-3-3. Infrared transmittance curves for glass Tedlar and Mylar. (ref. 5)

c. Heat Loss from the Cover

The main function of the cover, besides trapping the solar energy, is to provide the surface on which condensation can occur and to allow the latent heat of condensation to be released to the surroundings. For the best performance, the cover temperature should be low. There are two heat transfer mechanisms from the cover to the surroundings: convection and radiation. The radiation term is given by:

$$Q_{RC} = \varepsilon_c \cdot \sigma \, (T_c^4 - T_{sky}^4) \, A_c / A_w$$

Where: A_c, A_w, ε_c, T_c and T_{sky} are the cover surface area, water surface area, glass IR emissivity, cover temperature and effective sky temperature respectively. Radiation heat loss, Q_{RC} , as well as all other heat fluxes in this work are per unit surface area (1 m^2) of brine (W / m^2).

The effective sky temperature is frequently taken as 5 to 10 K below the ambient temperature, and the sky is treated as a blackbody. However, for the present study, the relation for T_{sky} by Swinbank (from ref. 4) has been used:

$$T_{sky} = 0.00552 \cdot T_a^{1.5}$$

Where temperatures are in degrees Kelvin. Probably, a more accurate result can be obtained using expression proposed by Bliss (from ref. 4):

$$T_{sky} = T_a \left(0.8 + \frac{T_{dp} - 273}{250} \right)^{1/4}$$

This requires T_{dp} (dew point temperature) and thus is not used in this work.

The convective term is somewhat more difficult to estimate, since the convective heat transfer coefficient, h_c , depends on several parameters: wind velocity, surface roughness, geometric shape of the solar still and air turbulance. Numerous experimental measurements have been made, some of them for geometries typical of solar stills. Several expressions are presented on figure 2-3-4 for better comparison . (equations given in ref. 4):

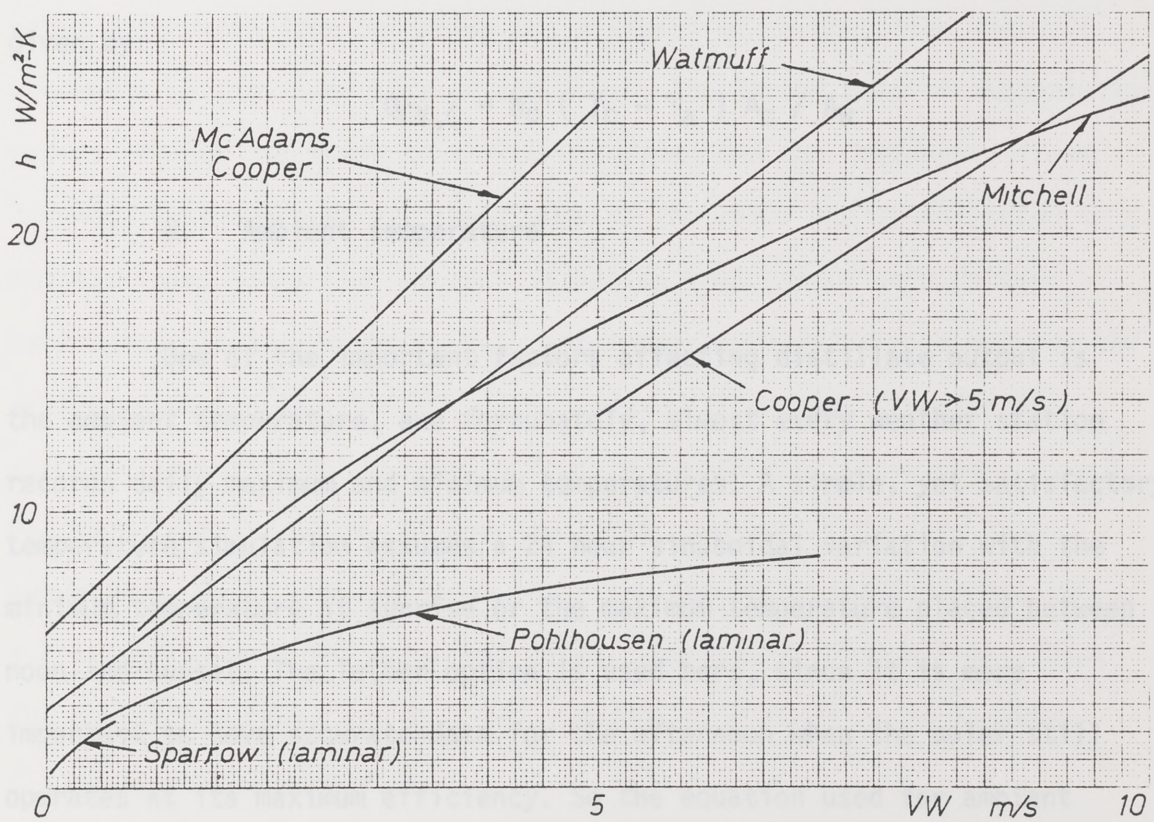

Figure 2-3-4. Convective heat transfer coefficient adapted for solar still geometries and dimensions. (ref. 4)

In this work, Mitchell's expression for forced convection over buildings has been used:

$$h_c = \frac{8.6 \cdot V_W^{0.6}}{L^{0.4}}$$

Where V_W is wind velocity, and L is a lenght scale defined as:

$$L = (\text{ volume of the still })^{1/3}$$

So the convective heat transfer from the cover to the surroundings is given by:

$$Q_{CV,C} = h_c \, (T_c - T_a) \, A_c \, / \, A_W$$

d. Ambient temperature

One of the important factors affecting distillate output is the ambient temperature, and fortunately, almost every weather station records daily maximum and minimum temperatures. A simple, yet satisfactory temperature simulation assumes a 24 hour sinusoidal variation with the minimum temperature at sunrise or the maximum temperature placed between noon and sunset. The latter option is used here, since it is more important to have accurate data for the afternoon when the solar still operates at its maximum efficiency. So the equation used for ambient temperature is:

$$T_a = \frac{T_{max} + T_{min}}{2} + \frac{T_{max} - T_{min}}{2} \cos(0.2618(t - \frac{t_s}{4} - 12))$$

Where t is the 24 hour time of day, t_s is the daylenght, and T_{max} and T_{min} are the maximum and minimum ambient temperatures on a certain day.

2 - 4 Internal Heat Transfer

There are four modes of heat transfer inside the solar still: radiation from the brine surface to the cover, convection and evaporation from brine to cover, and conduction through the walls to the surroundings and through the base to the soil underneath.

The most important energy path is evaporation heat transfer, Q_E. Due to the partial vapor pressure difference in the still interior, water evaporates from the brine and diffuses up to the cover where it condenses on the inner side of the cover. The latent heat of condensation passes through the cover to the surroundings and the condensate flows downward to troughs at the lower edge of the cover and is collected in a storage tank. There are two main variables that affect evaporation: temperature of saline water, T_W , and temperature difference between the saline water and the cover, $T_W - T_C$. Evaporation heat transfer is directly proportional to both factors, although the latter one ($T_W - T_C$) has much less influence. At the same time, the heat transfers by convection, Q_{CV} , and radiation, Q_R , are dependent solely on the difference between the water and cover temperature. Figure 2-4-1 shows the energy fractions for Q_E , Q_{CV} , and Q_R as a function of T_W with ($T_W - T_C$) as a parameter.

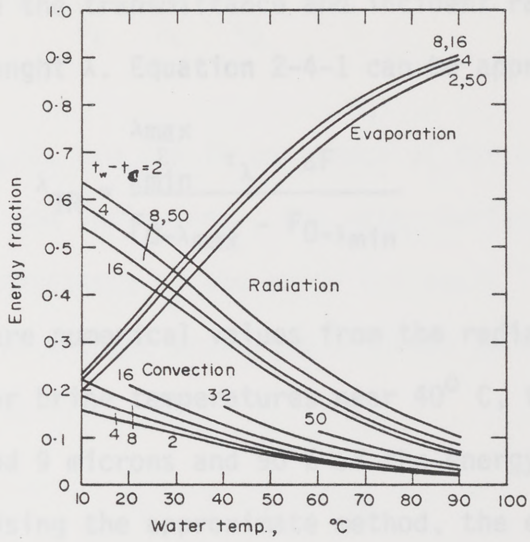

Figure 2-4-1. Energy fraction for combined evaporative, radiative and convective heat transfer. (from ref. 6).

a. Radiative Heat Transfer

Usually, the average daily temperature of the brine is around 40^{0} C and the water surface radiates heat to the cover which is 5 to 10^{0} C lower in temperature. In the case of glass covers all the internal radiation from the brine is absorbed by or reflected back from the glass. Plastic films, as mentioned earlier, transmit a portion of the infrared radiation from the brine and either absorb or reflect back the balance. The fraction of radiation transmitted through the cover can be calculated by:

$$\tau_{IR} = \frac{\int_{\lambda=0}^{\infty} \tau_{\lambda} \cdot i_{\lambda} \cdot d\lambda}{\int_{\lambda=0}^{\infty} i_{\lambda} \cdot d\lambda} \qquad (2\text{-}4\text{-}1)$$

Where τ_{λ} and i_{λ} are the transmittance and incident radiation energy from the brine at wavelenght λ. Equation 2-4-1 can be approximated by:

$$\lambda_{IR} = \frac{\sum_{\lambda min}^{\lambda max} \tau_{\lambda} \cdot \Delta F}{F_{0-\lambda max} - F_{0-\lambda min}}$$

Where ΔF and $F_{0-\lambda}$ are numerical values from the radiation tables (ref. 7 for example). For brine temperatures near 40^{0} C, the maximum radiated energy occurs around 9 microns and 90 % of the energy is radiated between 4 and 30 microns. Using the approximate method, the estimated infrared transmittance would be:

$$\tau_{IR} = \frac{\sum_{\lambda=4}^{\lambda=30} \tau_{\lambda} \cdot \Delta F}{0.9}$$

The brine and basin liner are essentially at the same temperature, so the heat is radiated from the basin liner and the water to the cover and the side walls (the latter being neglectible). It is assumed for simplicity that the brine surface and cover behave like graybodies (semi-gray for the case of plastic cover). Thus, the radiation heat exchange between the brine and the cover is given by:

$$Q_R = (1 - \tau_{IR}) \cdot \sigma \cdot F_{W-C} (T_W^4 - T_C^4)$$

Where σ, T_W, T_C, τ_{IR} and F_{W-C} are the Stefan-Boltzman constant, water and cover temperatures, infrared transmittance for the plastic cover (τ_{IR} = 0. for glass) and shape factor respectively. The shape factor for two parallel plates is:

$$F_{W-C} = \frac{1}{\frac{1}{\varepsilon_C} + \frac{A_W}{A_C}\left(\frac{1}{\varepsilon_W} - 1 \right)}$$

Where ε_C, ε_W and A_W/A_C are the IR emittance of the cover, IR emittance of the combined brine and basin liner, and water surface to cover area ratio respectively. The emittance of the brine and basin liner is usually in the neighborhood of 0.95 and the emittance of glass is also about 0.95. The emittance of plastic film is:

$$\varepsilon_C = 1 - \rho - \tau_{IR}$$

Where ρ (reflectance) is around 0.05. The water to cover area ratio, A_W/A_C depends on the slope of the cover which is between 10^o and 20^o and results in A_W/A_C being between 0.98 and 0.94. All these values yield a shape factor F_{W-C} of about 0.9 which is a good estimation for a glass covered still in the absence of actual data. Thus the simplified equation is used herein:

$$Q_R = 0.9 \cdot \sigma \left(T_W^{\,4} - T_C^{\,4} \right)\cdot\left(1 - \tau_{IR} \right)$$

In this prediction of Q_R, no allowance has been made for absorption of radiation by the humid air inside the still. A more detailed simulation was carried out by Cooper (ref. 3 and 6) who showed that although the radiation heat transfer can be reduced by as much as 20 % by this mechanism, the convective heat transfer increases, resulting in a negligible change in the evaporative heat transfer mode.

b. Convective Heat Transfer

Inside the still humid air exchanges heat from the water surface to the cover by natural convection. For this mode of heat transfer Dunkle (from ref. 4) suggests that the normal Rayleigh number be modified to account for bouyancy effects resulting from simultaneous heat and mass transfer. The bouyancy term in the Grashof number is thus modified by the density gradient caused by the composition gradient. For the solar still geometry, the relationship between Nusselt and Rayleigh number is:

$$Nu = 0.075 \cdot Ra^{1/3} \qquad \text{2-4-2}$$

Where the temperature difference in the Rayleigh number is an equivalent temperature difference which accounts for the density difference due to the water vapor concentration difference:

$$\Delta T = (T_W - T_C) + \left(\frac{P_W - P_C}{268\ 800 - P_W} \right) \cdot T_W \qquad \text{2-4-3}$$

Where temperatures are in Kelvins and pressures are in Pa. The quantities P_W and P_C are the vapor pressures of water at the brine and cover temperatures respectively.

The vapor pressure in the temperature range from 10 to 150^{o} C from the empirical expression given by Keenan and Kays (from ref. 6) , has been modified here for SI units to be:

$$P = 2.21 \cdot 10^{7-\left(\frac{X}{T} \left(\frac{a + b\,X + c\,X^3}{1 + d\,X} \right) \right)}$$

Where T is temperature in Kelvins and X=647.27 - T . The constants a, b, c and d are: 3.2437814, $5.86826 \cdot 10^{-3}$, $1.1702379 \cdot 10^{-8}$, and $2.1878462 \cdot 10^{-3}$ respectively. Using equations 2-4-2 and 2-4-3 as well as the above expression for P, the convective heat transfer coefficient h_{cv} in the still is:

$$h_{cv} = 0.884 \left(T_w - T_c + \left(\frac{P_w - P_c}{268\,800 - P_w} \right) \cdot T_w \right)^{1/3}$$

and the convective heat transfer between the basin and the cover is:

$$Q_{CV} = h_{cv} \cdot (T_w - T_c)$$

The convective heat transfer, Q_{CV} , is the smallest among the internal heat transfer modes and it varies from 25 to 5 percent of combined Q_E , Q_{CV} , and Q_R as the water temperature increases.

c. Evaporative Heat Transfer

Energy transport by evaporation-condensation is the most important mechanism occuring in stills because it is directly related to distillate output. The evaporation rate can be found by analogy between heat and mass transfer. The derivation of the equation for evaporation rate was done by Dunkle (from ref. 4) and is adapted here for the SI system of units:

$$Q_E = 6.9 \cdot 10^{-9} \cdot Q_{CV} \frac{P_W - P_C}{T_W - T_C} \cdot h_{fg}$$

where h_{fg} is the latent heat of vaporization given by:

$$h_{fg} = 3.16 \cdot 10^{6} - 2407 \cdot T_W$$

where the brine temperature, T_W , is in Kelvins.

Although evaporation heat transfer is approximately linearly proportional to convective heat transfer for low brine temperatures, at higher brine temperatures the evaporation term becomes relatively large compared to convection, due to the marked increase in vapor pressure difference (see fig. 2-4-1).

The distillate output rate is simply:

$$\dot{m} = Q_E \,/\, hfg$$

d. Leakage

In any well designed and well built solar still, heat losses by leakage should be negligible. Still, they occur in every commercial plant during its operation and it is quite costly to eliminate them completely. A good estimate according to several authors (ref. 1) is to assume the heat leakage to be five percent of combined convective and evaporative heat transfer:

$$Q_L = 0.05 \cdot (Q_{CV} + Q_E)$$

Another fact that has been observed is that heat loss by leakage inevitabely becomes larger as the still ages. This is especialy true for plastic-covered stills.

e. Enthalpy Change

Incoming sea water enters the still at ambient temperature (as treated in this work) and leaves the still at the brine operating temperature, T_W . For the continous flow solar still it is necessary to continuously dispose of a quantity of brine, and the optimal rate of water flow for maximum efficiency is approximalely twice the distillate flow rate. That is, 50 % of the incoming water will be evaporated and 50 % will be disposed. Thus, the salinity of disposed brine will be double that of the make-up brine. If the brine is operated at too high a concentration, a thin film of sodium chloride (NaCl) and other mineral salts will develop on the brine surface and supress furthur evaporation.

The mass balance for the still is:

$$\dot{m} = \dot{m}_e + \dot{m}_{out}$$

and

$$\dot{m}_e = \dot{m}_{out}$$

also

$$\dot{m}_e = Q_E \ / \ h_{fg}$$

Based on these equations, the enthalpy change ($\dot{H} = \dot{H}_{w,i} - \dot{H}_{w,o}$) can be derived:

$$\Delta\dot{H} = \frac{Q_E}{h_{fg}} \cdot C_w \ (2\ T_a - T_c - T_w)$$

where C_w is the specific heat of water, and assumed to be constant over the concentration range of still operation.

2 - 5 Side Heat Losses

The heat loss through the side of the still is difficult to estimate correctly, since there are a number of factors affecting it. Usually, the sides of a still are short; varying from a few centimeters to around 30 cm. Heat is transferred by radiation from the sides to the sky, to ajacant stills and to the ground. Convective heat loss is in the form of natural and forced convection from the vertical walls. The walls also absorb some solar energy directly and by reflection from the walkways. Fortunately, as the side walls are small, the side wall contribution to the total heat loss per square meter of brine surface is relatively small compared to the other terms. Thus, the error involved in estimating the overall heat loss coefficient from the sides, h_s , should not seriously affect the total heat balance.

In some of the first articles on solar still performance, the side heat loss term was combined with the base heat loss into one term called edge and bottom loss. This loss has been subject to considerable differences of opinion. Cooper (ref. 6) developed a digital simulation program for a solar still in transient operation and treated the base and side heat losses separately. For the side heat losses he assumed the loss coefficient, h_s , to be 0.5 Btu/F-hr per square foot of base area (2.85 W/m^2-K) or 3.9 Btu/F-hr per square foot of walls area (22.1 W/m^2K) with the temperature difference being that between the brine and ambient ($T_w - T_a$). In this work, both the conduction resistance of the walls and the convection and radiation resistance from the wall exteriors to the surroundings are included in determining the side losses. The heat loss coefficient, h_s , is taken as 30 W/m^2-K of the side wall area, based on the temperature difference between the outside surface of the walls and ambient temperature. This value fits the experimental results found in Australia (ref. 3).

The equation for side heat losses is given by:

$$Q_S = \frac{A_S / A_W}{1/h_S + d_S/k_{sid}} (T_W - T_a)$$

where d_S and k_{sid} are the thickness and conductance of the side walls. A_S/A_W is the ratio of the side wall surface area to brine surface area.

This estimation of the side heat loss coefficient, h_S , is not accurate for every still design, but a more detailed theoretical approach would require much more detailed analysis which is beyond the scope of this work.

2 - 6 Base Heat Flow

Heat flow from the still to the ground plays a very significant role in overall efficiency of solar stills. Although a large portion of the heat that is lost to the ground during the day comes back during the night (making net heat loss relatively small), the diurnal variation of the base heat flow is important in optimizing the output. Reducing the base heat losses (as well as all the other heat losses) during the time of high insolation, will always increase the distillate output. The degree of productivity improvement obtained by decreasing the base heat loss depends on the depth of the brine. As seen from figure 2-6-1, during sunny days, distillate output for shallow stills can be increased by 20 to 30 % using insulation on the bottom of the still. However, for a deep basin it is seen that there is little effect on productivity.

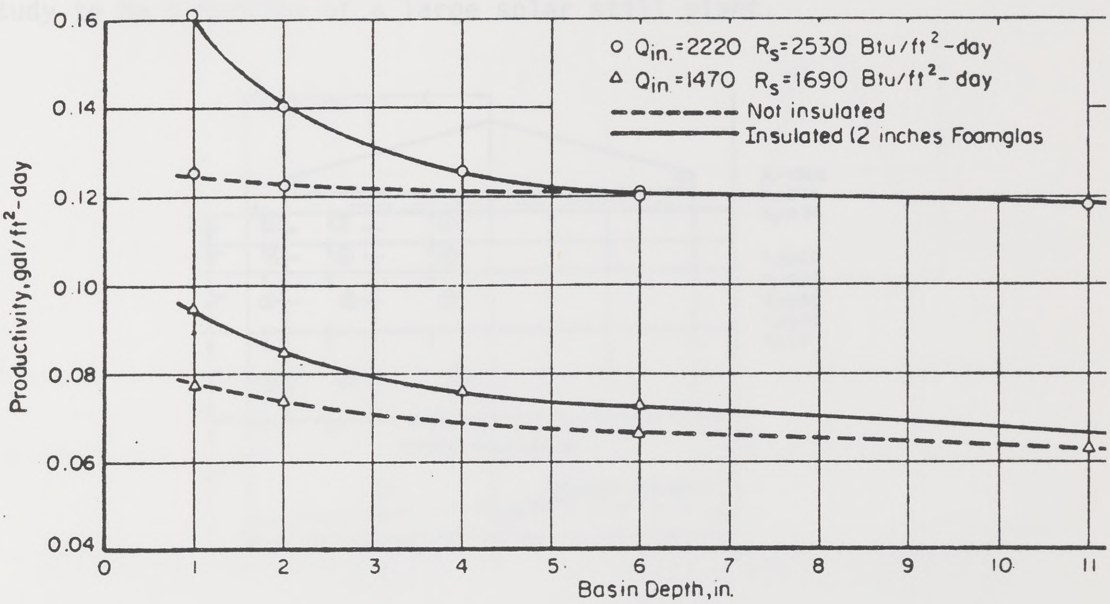

Figure 2-6-1. Effect of basin depth and insulation on productivity of Battelle laboratory still. (ref. 1).

The base heat loss coefficient, U_b , has been treated as constant in some of the first articles on solar still performance. The heat loss was calculated simply by multiplying U_b by the temperature difference between the brine and some constant soil temperature (T_w - T_s). Besides the fact that this approach is not very accurate, it represents poorly the base heat flux variation during the day and night. Using this model, heat flows from the still to the ground all the time, while in reality, during the night the still gains heat from the ground rather than loses it. Cooper (ref. 6), developed a detailed finite difference solution for the base heat flow using a 2-D transient conduction solution. He devided the ground beneath the still into 24 elements (fig. 2-6-2), assumed the soil to have homogenous properties and the section under study to be a portion of a large solar still plant.

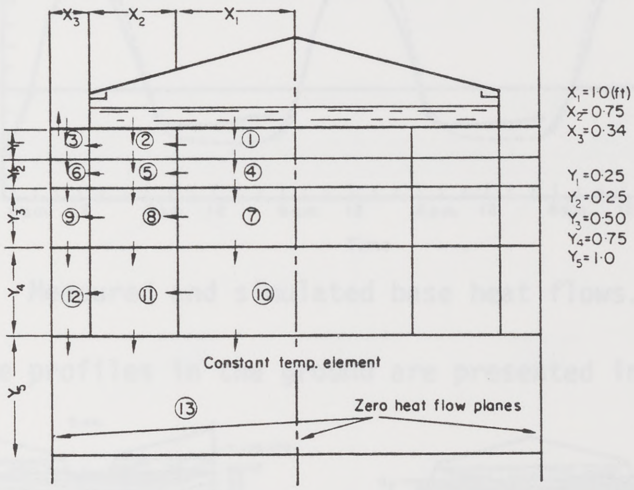

Figure 2-6-2. Ground element distribution beneath still. (ref. 6)

Later on, CSIRO built an experimental solar still plant in Perth, Australia, that was well instrumented with thermocouples and heat flow meters in the ground (fig. 2-6-3).

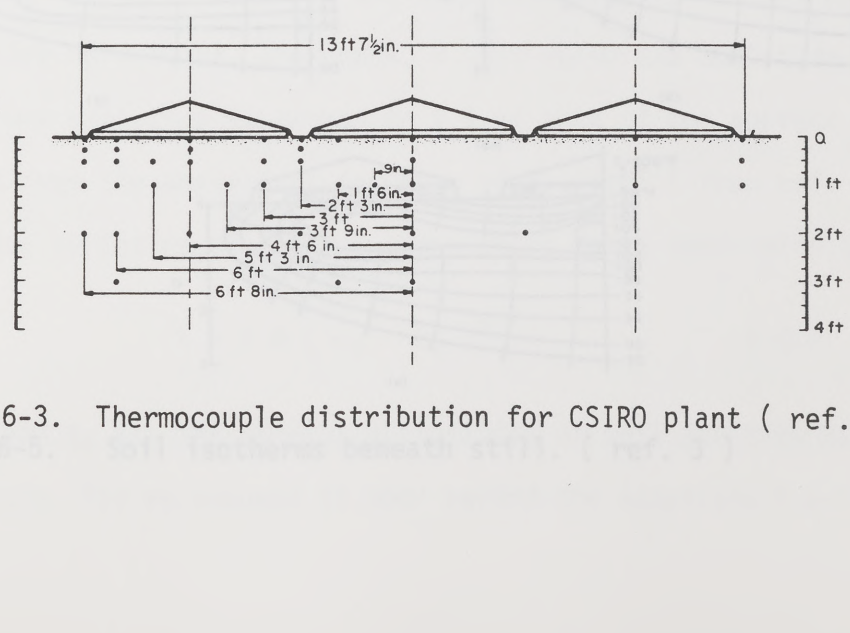

Figure 2-6-3. Thermocouple distribution for CSIRO plant (ref. 3)

The experimental results were in very good agreement with the predicted base heat flow as shown on figure 2-6-4.

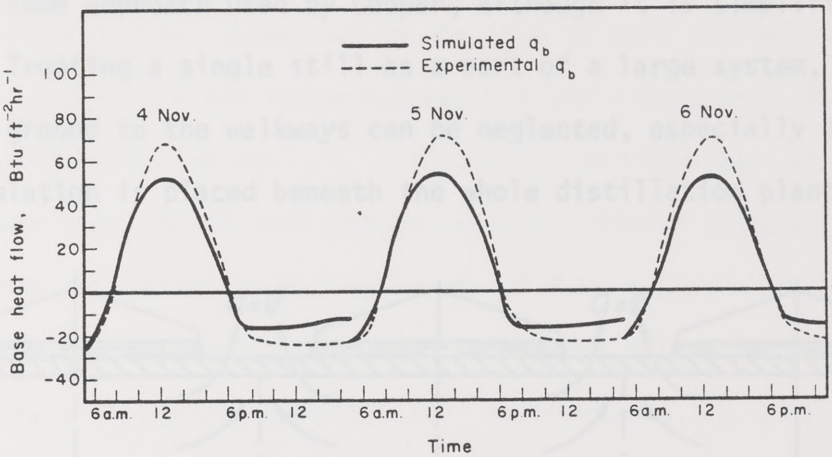

Figure 2-6-4. Measured and simulated base heat flows. (ref. 3)

The temperature profiles in the ground are presented in figure 2-6-5.

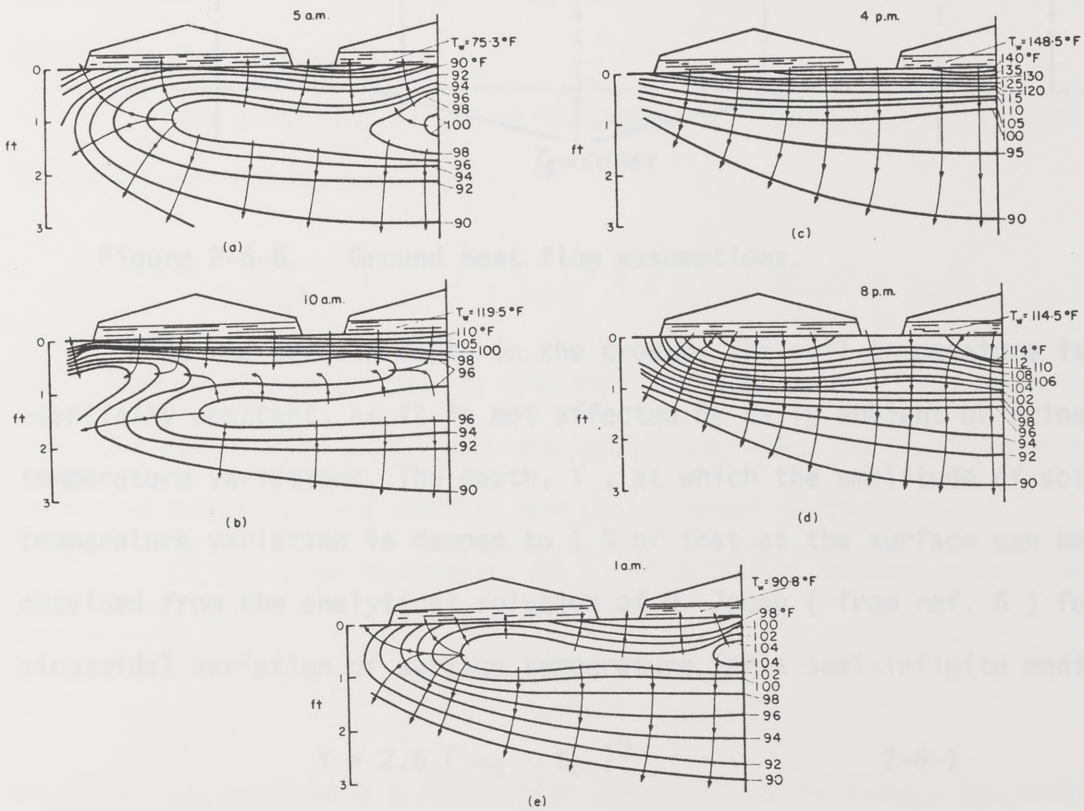

Figure 2-6-5. Soil isotherms beneath still. (ref. 3)

The method of predicting the base heat flow used here is based upon the same approach used by Cooper, although it is simplified to a 1-D problem. Treating a single still as a part of a large system, heat flow from the ground to the walkways can be neglected, especially in the case when insulation is placed beneath the whole distillation plant (fig. 2-6-6).

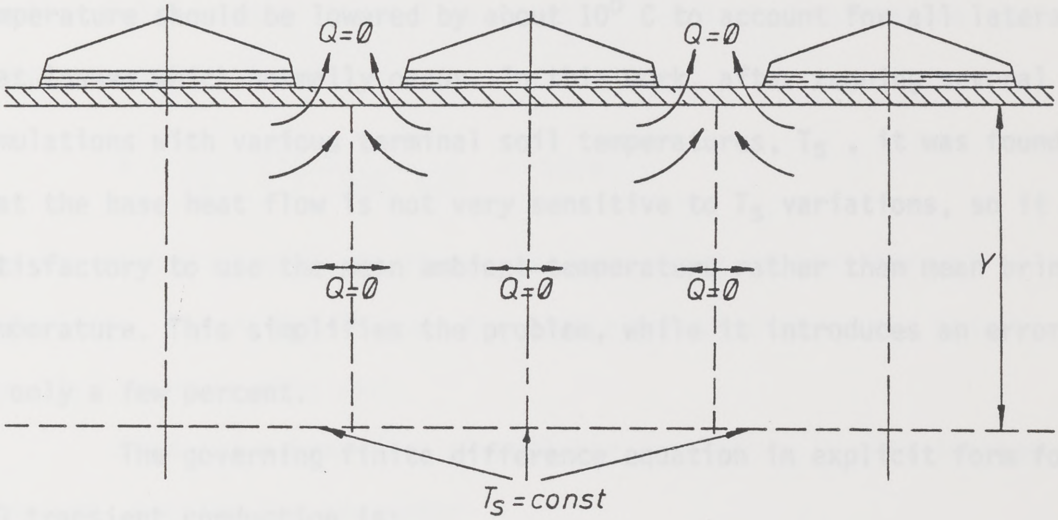

Figure 2-6-6. Ground heat flow assumptions.

At the certain depth in the ground, the soil temperature is esentially constant, as it is not affected by daily ambient or brine temperature variations. The depth, Y , at which the amplitude of soil temperature variation is damped to 1 % of that at the surface can be obtained from the analytical solution of M. Jacob (from ref. 6) for sinusoidal variation of surface temperature for a semi-infinite medium:

$$Y = 2.6 \ (\alpha_S \cdot t_C)^{\frac{1}{2}} \qquad \text{2-6-1}$$

where α_S and t_C are the thermal diffusivity of soil and time period respectively. For an assumed 24 hour period the equations 2-6-1 becomes:

$$Y = 764.2 \cdot \alpha_s^{\frac{1}{2}}$$

This depth will vary, depending on the type of soil and moisture content, but it is usually in the range between 0.2 and 1.0 meters. At this depth, the temperature of the soil, T_s , should be near the mean brine temperature over the 24 hour period. However, Cooper suggests that this temperature should be lowered by about 10^o C to account for all lateral heat losses which normally occur. In this work, after running several simulations with various terminal soil temperatures, T_s , it was found that the base heat flow is not very sensitive to T_s variations, so it is satisfactory to use the mean ambient temperature rather than mean brine temperature. This simplifies the problem, while it introduces an error of only a few percent.

The governing finite difference equation in explicit form for 1-D transient conduction is:

$$T_m^{p+1} = \frac{\alpha \cdot \Delta t}{\Delta y^2} (T_{m+1}^p + T_{m-1}^p) + (1 - \frac{2\alpha \cdot \Delta t}{\Delta y^2}) T_m^p$$

where superscript p designates present time and p+1 one time step, Δt , into the future. The subscripts designate the node. The terms Δy and α represent vertical node spacing and soil thermal diffusivity.

If the time increment, Δt , and distance between nodes are chosen such that:

$$\frac{\Delta y^2}{\alpha \cdot \Delta t} = 2 \qquad \text{2-6-2}$$

the temperature of node m after time increment Δt is simply the aritmetic average of the two adjacant nodal temperatures at the begining of the time increment. That is:

$$T_m^{p+1} = \frac{T_{m+1}^p + T_{m-1}^p}{2}$$

After the first several simulations it was found that a reasonable time increment, Δt , is 15 minutes (900 s), for which no oscillations occur. Thus the distance between nodes, Δy , is given by equation 2-6-2, and distance Y by equation 2-6-1 which gives the necessary number of nodes N:

$$N = \frac{Y}{\Delta y} = \frac{764.2 \cdot \alpha^{\frac{1}{2}}}{(2 \cdot 900 \cdot \alpha)^{\frac{1}{2}}} = 18.0$$

Thus the number of nodes is always 18, regardless of soil thermal diffusivity. Figure 2-6-7 shows the complete nomenclature for base heat flow, Q_B , used in this work.

Conduction heat flow through the insulation is also treated as transient. Setting the parameter

$$\frac{\Delta y_{in}^2}{\alpha_{in} \cdot \Delta t} = 2$$

the node spacing in the insulation, Δy_{in} , for 900 s time steps is:

$$\Delta y_{in} = (1800 \cdot \alpha_{in})^{\frac{1}{2}}$$

where α_{in} is the insulation thermal diffusivity. Thus, the total number of nodes in the insulation, N_{in} , is:

$$N_{in} = (d_{in} / \Delta y_{in}) + 1$$

rounded to the next smallest integer, where d_{in} is the specified insulation thickness. However this value of insulation thickness must be corrected, since rounding the N_{in} to an integer introduces an error. Thus:

$$d_{in} = (N_{in} - 1) \cdot \Delta y_{in}$$

so insulation thickness can acquire only discrete values to avoid the possible errors.

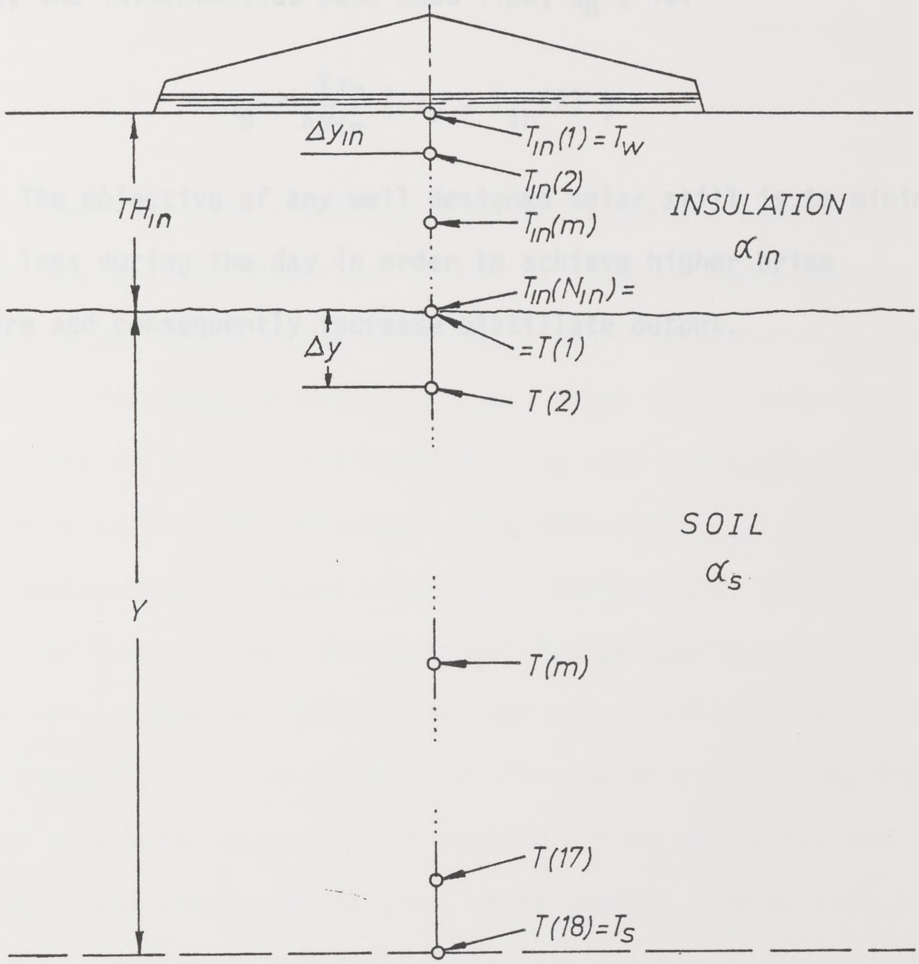

Figure 2-6-7. Transient temperature nomenclature beneath still.

The governing equation for transient insulation temperatures is:

$$T_{m,in}^{p+1} = (T_{m-1,in}^{p} + T_{m+1,in}^{p}) / 2$$

This equation is also valid for the temperature between the insulation and the ground ($T_{in,Nin} = T_1$) since for both parameters $\Delta y^2/\alpha \cdot \Delta t = 2$.

$$T1^{p+1} = (T_{in,Nin}{}^{p} + T_2{}^{p}) / 2$$

Therefore, the instantanious base heat flow, Q_B , is:

$$Q_B = \frac{k_{in}}{\Delta y_{in}} (T_w - T_{in}(2))$$

The objective of any well designed solar still is to minimize this heat loss during the day in order to achieve higher brine temperature and consequently increase distillate output.

3. CONSTRUCTION

In this chapter, the generall classification of design types and materials for construction will be given. Also, three standard (reference) types are proposed here.

3 - 1 Standard Stills

There are many different solar still designs used around the world and they are well described in ref. 1. Some of these designs showed over longterm use better performance and durability compared to others, due to design features and materials used. Since direct comparison among such a variety of solar stills would make it very difficult to distinguish which factors affect the performence more than others, it is suggested here to propose three standard solar still designs with their particular materials for construction. The choice of design type has been made upon comparing only commercial large basin-type solar stills, thus excluding any experimental stills. In general, stills can be divided into those with glass or plastic covers. Glass covered stills can be divided into the double sloped and single sloped type, while plastic covered stills are usually double sloped or inflated (using air blowers). Figure 3-1-1 shows those four configurations. There are other designs but most are variations on one of those four basic designs. Among these four, all of them but the inflated type showed satisfactory performance over the years.

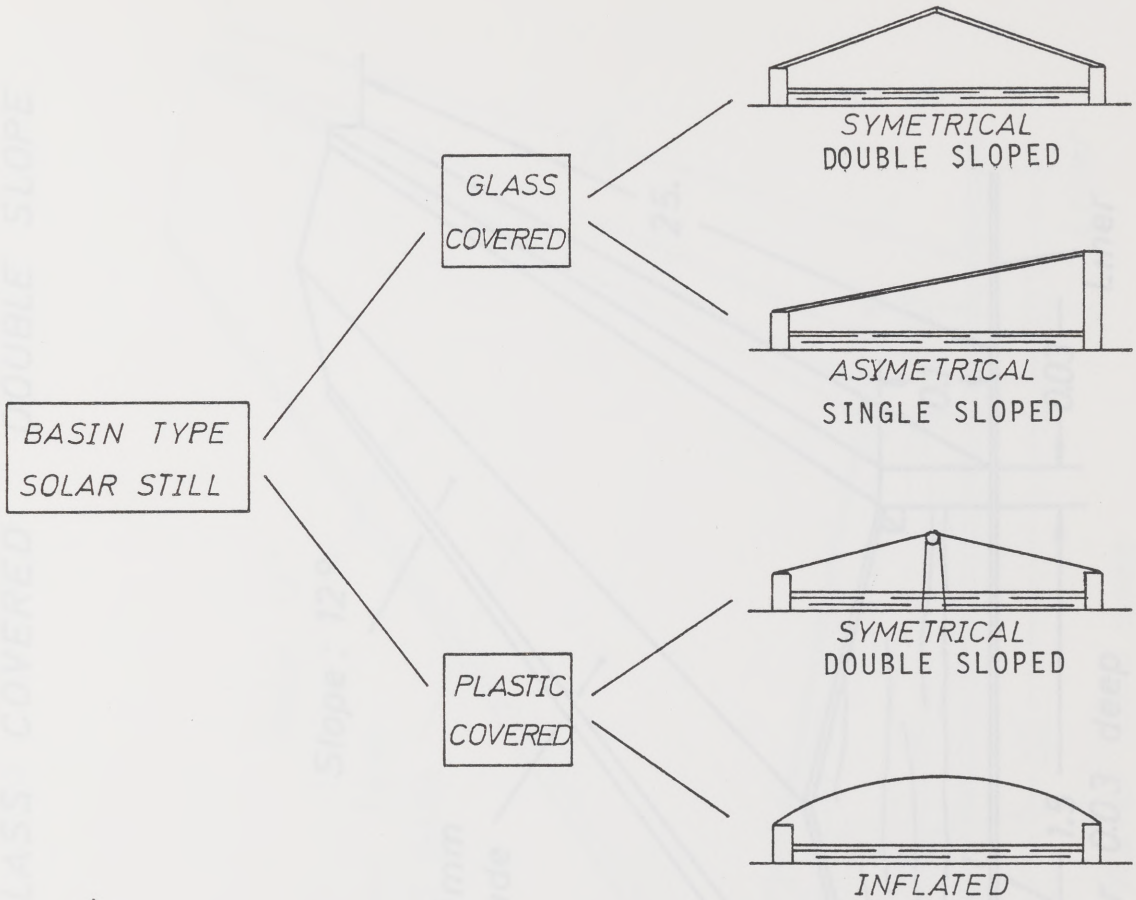

Figure 3-1-1. Four basic still designs.

The inflated type, although very simple to construct, has usually exhibited higher leakage rates and almost always exhibited the problem of the cover collapsing during heavy rain or wind. For these reasons, the inflated type is not considered here. Simplified schematics of the three proposed designs are shown in figures 3-1-2, 3-1-3 and 3-1-4.

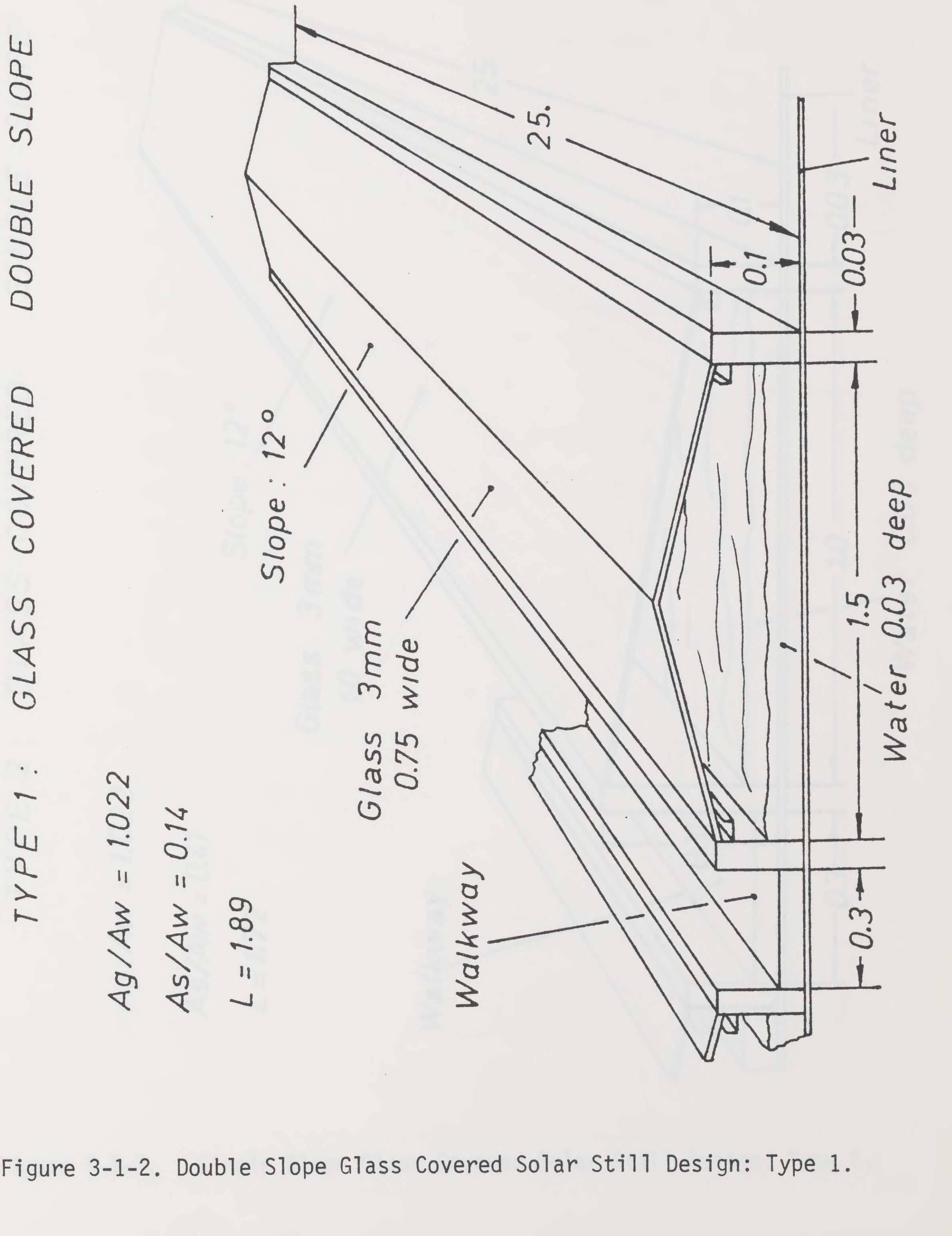

Figure 3-1-2. Double Slope Glass Covered Solar Still Design: Type 1.

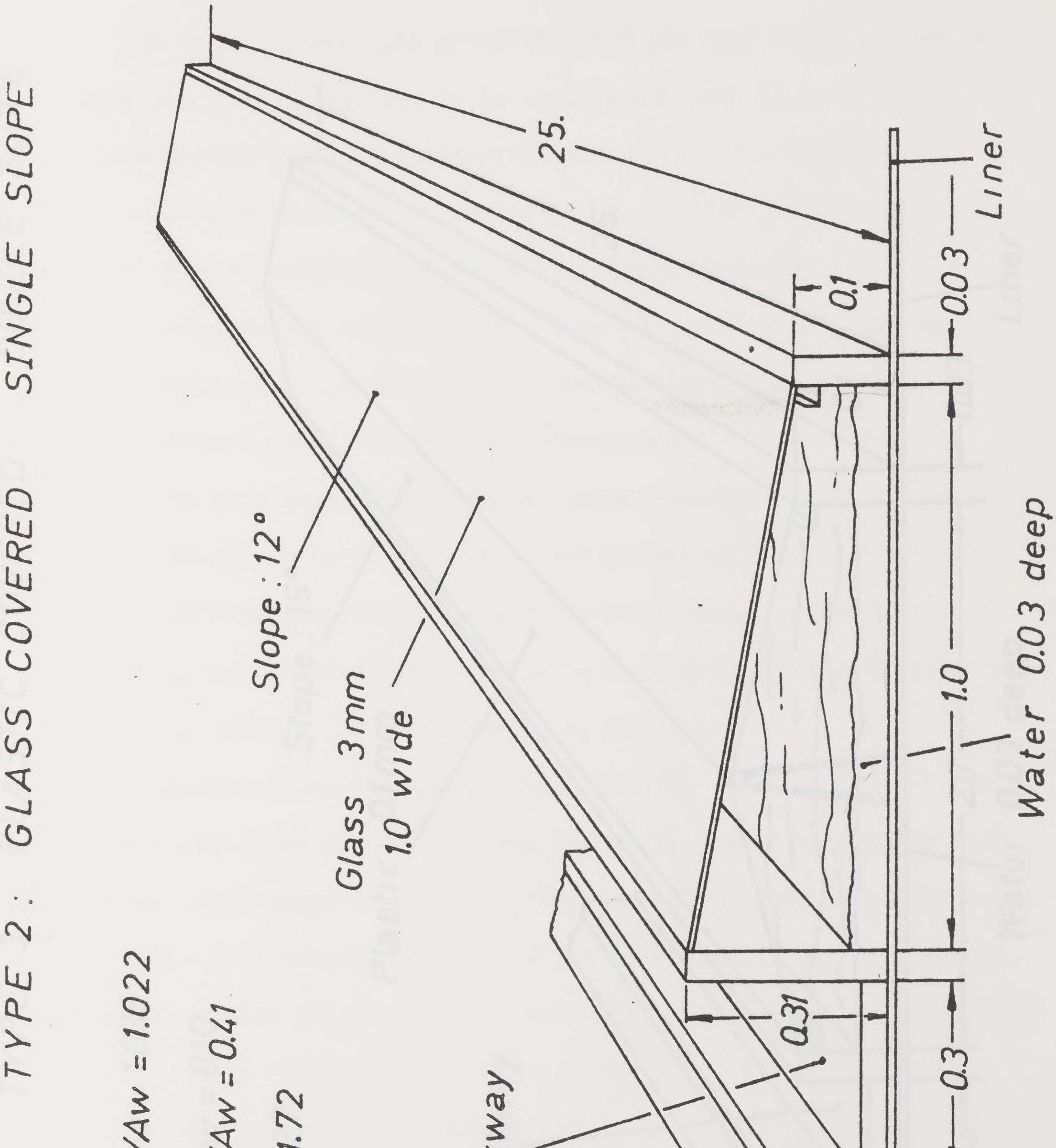

Figure 3-1-3. Single Slope Glass Covered Solar Still Design: Type 2.

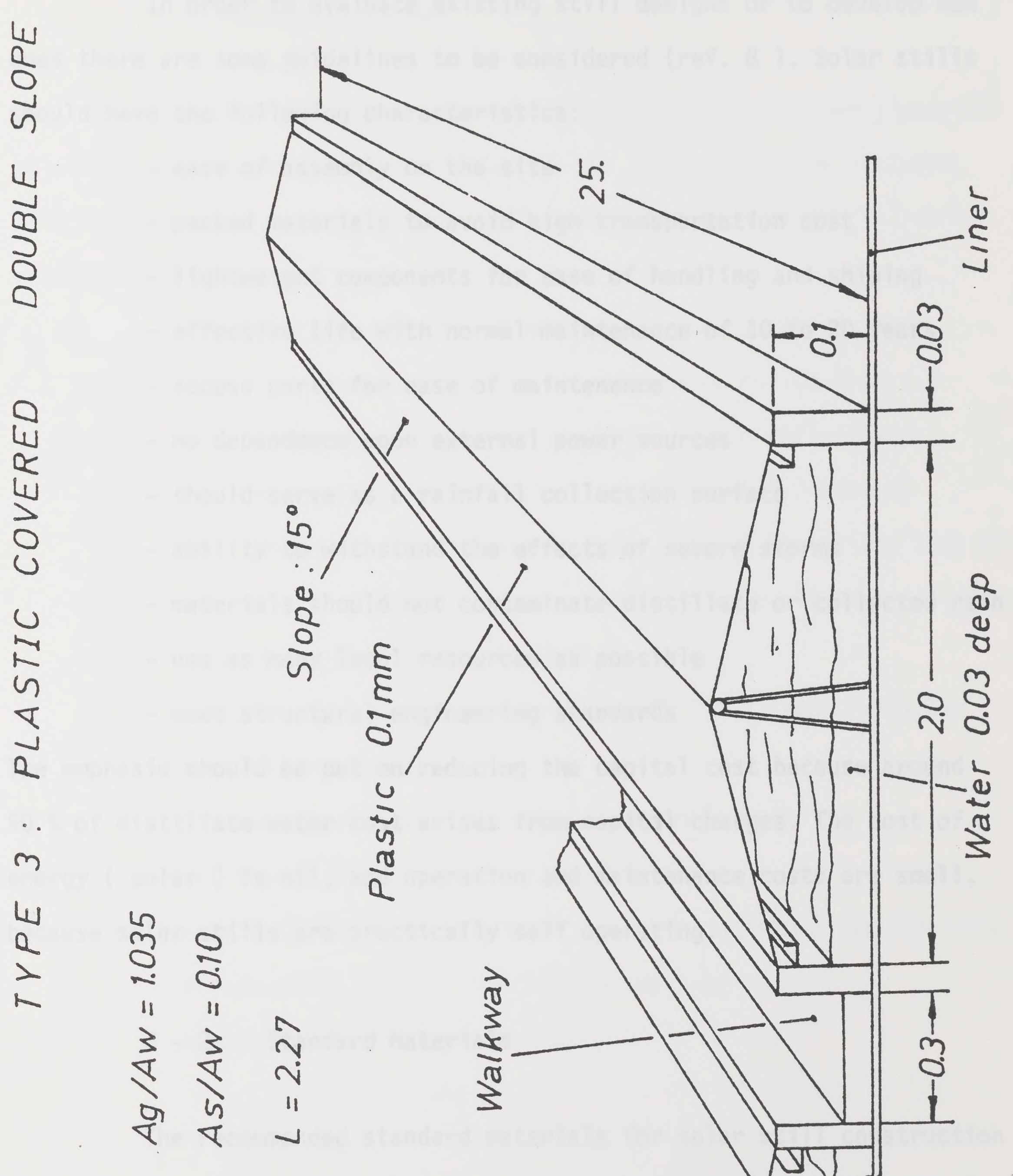

Figure 3-1-4. Double Slope Plastic Covered Solar Still Design: Type 3.

In order to evaluate existing still designs or to develop new ones there are some guidelines to be considered (ref. 8). Solar stills should have the following characteristics:

- ease of assembly on the site
- packed materials to avoid high transportation cost
- lightweight components for ease of handling and shiping
- effective life with normal maintenance of 10 to 20 years
- access ports for ease of maintenance
- no dependence upon external power sources
- should serve as a rainfall collection surface
- ability to withstand the effects of severe storms
- materials should not contaminate distillate or collected rain
- use as many local resources as possible
- meet structural engineering standards

The emphasis should be put on reducing the capital cost because around 90 % of distillate water cost arises from capital charges. The cost of energy (solar) is nil, and operation and maintenance costs are small, because solar stills are practically self operating.

3 - 2 Standard Materials

The recommended standard materials for solar still construction are taken from ref. 1 and ref. 8, and they have been chosen on the basis of their performance, durability and cost. The most important factor is durability because, ideally, stills must operate with minimal maintenance and repair costs in order to produce fresh water at competetive prices.

a. Transparent Cover

The cover has three major functions: to collect distillate and rainfall, to transmit solar radiation to the interior and to minimize heat losses. Ideal materials for still covers should meet the following requirements (ref. 8):

- withstand the effects of weather (wind, sunshine, rain)
- have high transmittance in the shortwave region from 0.3 to 3.0 microns (low solar absorptance and reflectance)
- be almost opaque to radiation beyond about 3.0 microns
- have low water absorptance on both sides (distillate and rain)
- not possess electrostatic properties (to avoid concentration of dust on the outside surface)
- withstand the temperatures up to 80° C and large relative humidity variations
- ability to withstand the abuses of small animals
- ability to withstand winds to 45 m / s

There are really only two materials that can be recommended for the cover

- window glass 2.5 - 3.0 mm
- wettable Tedlar 0.1 mm

b. Basin Liner

The basin liner serves as an absorbing surface for the incoming radiation as a container for the brine. Basin liner materials should have the following characteristic:

- impervious to water
- radiation absorptance of the liner up to 95 %
- fairly smooth to retard deposition and faciliate cleaning
- not deteriorate or decompose on contact with normal soils
- withstand the effects of hot (80 to 100^{o} C) water for extended periods
- not emit any gases or vapor which could contaminate the distillate

the following materials have been successfully used:

- Butyl rubber	0.5 mm
- Asphalt mat	0.5 mm
- Black Polyethylene	0.2 mm
- Roofing asphalt	over concrete

c. Structural Materials

These materials are used to form the sides of the basin and should possess the following properties:

- be resistant to saline water and the atmosphere
- covered with protective coating inside basin
- be sufficiently heavy to anchor the stills during heavy winds
- side components available in series of sizes for easy assembly and disassembly on site

A variety of materials can be used successfully for this purpose:

- Concrete
- Concrete blocks
- Aluminium
- Galvanized metal
- Redwood

d. Sealants

Sealants are used to seal sections of the transparent cover to each other and to the supporting structure, and should have the qualities:

- show slow degradation due to water and humid air
- intercept only a minimum amount of solar energy
- easy to use on site
- withstand the effects of wind up to 45 m/s

Some commonly used sealants are:

- Silicone rubber
- Asphalt caulking compound
- Butyl rubber extrusions

e. Insulation

The insulation materials are used beneath the basin liner to reduce ground heat losses. Very often, the insulation is eliminated and the basin liner is placed directly on the ground. One of the objectives considered in this work is to determine under what circumstances is basin insulation justifable.

If insulation is used, the materials should have the following properties:

- lightweight and ability to support the basin
- waterproof and water impermeable
- ability to withstand temperatures up to 80^{o} C
- not be degraded by soil

Satisfactory insulation materials include:

- Sand
- Concrete
- Polystyrene

f. Auxiliaries - troughs, piping, reservoirs

All of the plumbing and reservoirs materials are in direct contact with either fresh water or saline water and should:

- have protective coatings or be stainless to avoid contamination or damage to the system
- be continous, to avoid internal joints which are difficult to maintain

Troughs serve to collect the fresh water from the cover and the best materials are:

- Stainless steel
- Butyl rubber (lining)
- Black Polyethylene (lining)

Piping, for saline water as well as for fresh water, may be made of:

- P V C
- A B S
- Asbestos cement (for saline water only)

Reservoirs are of three types: for fresh water, for rainfall and for saline water. The distillate reservoir should have at least three times the maximum daily production capacity. The rainwater reservoirs should be sized to short term rain intensities. The reservoirs should be protected against contamination from dirt, dust, animals and from salt water overflow. The water should be carefully handled and sand-filtered if necessary. The reservoir materials commonly used are:

- Concrete
- Masonry

4. ECONOMICS

This chapter provides the economics model for estimating the cost of fresh water produced by solar stills.

4 - 1 Comparison with other Techniques

To evaluate the economics of producing fresh water from solar stills, the costs involved must be compared with the alternative methods of supplying fresh water. One of the alternatives is the utilization of fresh water obtained from natural sources, and the other is the production of distillated water using nonsolar processes.

There are several characteristics of a location to enhance the prospects for solar distillation:

- adequate availability of saline water
- arid areas where inexpensive conventional sources of energy are not readily available
- adequate level of solar radiation and high daily temperatures
- areas where annual rainfall does not exceed 600 mm
- land is available and is inexpensive

In any case, neither solar nor any other process should be considered untill full exploitation has been made of natural fresh water sources: rainwater, surface and ground water. Among the distillation processes, it has been shown that for small fresh water demands (up to 200 m^3/day), the basin type solar still is more economical than other distillation processes (see fig. 4-1-1).

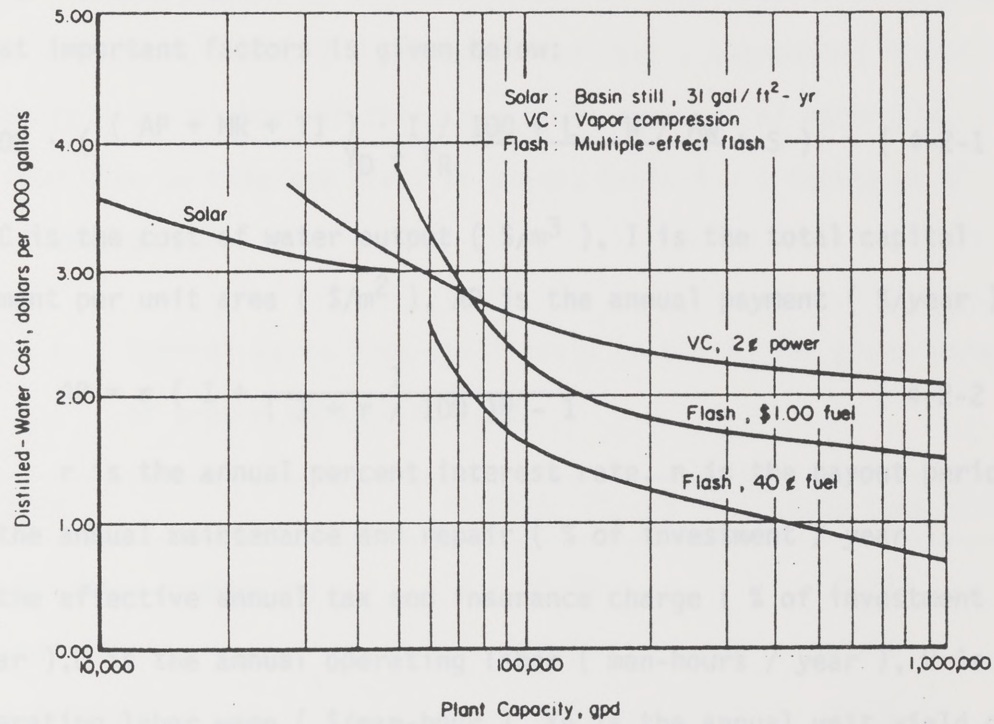

Figure 4-1-1. Distilled water cost comparison in U.S.A. in 1966 (ref. 1)

4 - 2 Cost of Water Output

The cost of water produced in solar stills depends on three major factors:

- total capital cost of the plant
- operation, maintenance and repair expenses
- the performance or distillate output from the facility

There are several minor factors which affect the water cost as well: cost of electricity for pumping, cost of rainfall collection, cost of storing the water etc.

It is common to express the cost of water output in $\$/m^3$ (or $/1000 gal). The equation that relates the cost of water production to the most important factors is given below:

$$C = 1000 \cdot \left(\frac{(AP + MR + TI) \cdot I / 100 + L \cdot W / A_W}{Y_D + Y_R} + S \right) \qquad (4\text{-}2\text{-}1)$$

where C is the cost of water output ($\$/m^3$), I is the total capital inwestment per unit area ($\$/m^2$), AP is the annual payment (%/year)

$$AP = r \left(1 + \frac{1}{(1 + r / 100)^n - 1} \right) \qquad (4\text{-}2\text{-}2)$$

r is the annual percent interest rate, n is the payout period MR is the annual maintenance and repair (% of investment / year), TI is the effective annual tax and insurance charge (% of investment per year),L is the annual operating labor (man-hours / year), W is the operating labor wage ($/man-hour), Y_D is the annual unit yield of distillate water (l/m^2-year), Y_R is the annual unit yield of collected rainfall (usually around 80 % of total yearly rainfall; l/m^2-year) A_W is the area of solar still plant on which yield is based (m^2) and S is the cost of salt water supply ($/l of product).

4 - 3 Capital Cost

The total capital investment for a solar still plant is affected by sevefal factors, such as: the absolute size, type of still, cost of labor and materials etc. As it is somewhat difficult to estimate the total cost for every solar still plant, Lowand (ref. 8) proposed a standard procedure for costing applicable to all designs and all countries, and it is given in the appendix in the form of worksheets.

In the absence of actual quotes on the cost of materials for solar still construction, an estimation must be made. Useful data were compiled by Talbert (ref. 1) and corrected data (accounting for inflation only) are shown in table 4 - I. As the cost of materials varies from time to time and place to place, table 4 - I serves as a rough estimate only.

Table 4 - I. Typical basin type still costs in U.S.A. for plant size of around 5000 m^2 in 1982.

ITEM	MATERIAL ($\$/m^2$)	LABOR (man-h/m^2)
Layout, grading, compacting	0.25	0.22
Asphalt-mat liner	2.00	0.43
Concrete blocks	1.50	0.11
Precast concrete beams	4.75	0.27
Glass and asphaltic cement	5.25	0.27
Distillate trough materials	1.25	0.05
Piping and pumps	1.75	0.05
Storage tank	1.25	0.05
TOTAL	18.00	1.45

Listed on the next page are actual costs of several plants reported by their constructors. Values are taken from ref. 1 and adjusted for inflation for 1982.

U.S.A.	\$ 31.25 / m^2	- glass	4600 m^2
Australia	\$ 17.50 - 32.50 / m^2	- glass	
Greece	\$ 40.90 / m^2	- glass	8600 m^2
	\$ 43.75 / m^2	- plastic	1500 m^2
Spain	\$ 26.25 / m^2		900 m^2
Petit St. Vincent	\$ 53.25 / m^2	- plastic	100 m^2
India	\$ 20.00 / m^2	- glass	200 m^2
Tunis	\$ 22.00 - 31.00 / m^2		900 m^2
USSR	\$ 25.00 - 66.00 / m^2		2400 m^2

4 - 4 Operating Cost

Operating costs can be split into 5 categories:

a. Amortization and interest charges - AP

b. Annual maintenance and repair - MR

c. Taxes and insurance - TI

d. Labor for operating and supervising - L

e. Raw materials and energy cost - S

a. Amortization

There are several depreciation schedules; such as sinking fund, straight line, SYD, DDB etc, but for simplicity, the straight line method is considered here. The main parameter for determining the annual depreciation rate is the lifetime of plant. Glass covered solar stills are considered to have 20 years lifetime, thus resulting in an annual depreciation charge of 5 %. Plastic covered solar stills will generally have higher depreciation charges since the cover has to be replaced every 3 to 4 years.

Interest rates vary widely over the years and from country to country. Using the interest tables or equation 4-2-2 , depreciation and interest charges can be combined into a single factor AP.

b. Taxes and Insurance

Taxes and insurance which also vary from case to case include insurance for the plant and employees, and the taxes if the plant is not publicly owned. A good approximation (when actual data are lacking) is to assume taxes and insurance, TI , to be 1 % of unamortized investment per year.

c. Annual Maintenance and Repair

The combined maintenance and repair costs are nearly proportional to the size of the plant and thus, can be expressed as a percentage of the total capital investment. For a durable type solar still, the maintenance cost would be lower and can be taken as one or two percent of total investment. Plastic type solar stills, which are less durable, will require more repairs and MR is assumed to be between two and four percent.

d. Labor for Operating and Supervizing

This factor is relatively independent of plant size, and only a few man-hours a week are required. In places where the cost of labor is high, automatic controls and regulators should be used. It is assumed that approximately 200 to 250 man-hours per year are required for plant operation and inspection.

e. Raw Materials and Energy Cost

The only raw materials required are saline water and some chemical additives. Their cost is negligible. The energy cost for pumping saline water can be calculated knowing that a typical power requirement is between 4 and 4.5 W-h per m^3 of water per meter of lift. For optimal performance, 2 liters of saline water are needed for each liter of distillate output; thus the total energy cost for saline water transportation is:

$$S = 8.5 \cdot 10^{-6} \cdot h \cdot e \qquad (\$ / \text{liter of distillate})$$

where h is the lifting height in meters and e is the cost of electricity in \$/kWh. For a seaside solar still, this cost is very small due to small lifting height; but if brackish well water is used, the cost of pumping can be significant. However, this cost will be the same for all desalinization processes.

4 - 5 Distillate Output

There are considerable data on solar still productivity, and generally, most community-sized solar stills show similar performance. During clear sunny days, when the global solar radiation is of the order of 23. to 25 MJ/day, the average still will produce 3.5 liters of fresh water per square meter per day. Winter productivity is approximately 1 l/m^2-day for 10 MJ/day of solar input. The following equation may be used to calculate the productivity of a typical still with ± 25 % accuracy:

$$P = 0.0376 \cdot Q_T^{1.4} \qquad (l \,/\, m^2 \text{ - day })$$

where Q_T is global daily insolation on a horizontal surface.

Many other empirical equations for productivity estimation are presented in ref. 1 , some including the effect of water temperature as well as insolation. However, to optimize the solar still design and materials for construction, which is one of the objectives of this work, the complete simulation of still productivity needs to be carried out to find out how certain design parameters affect the productivity, and consequently the cost of water output.

5. APPLICATION

One example of optimizing the still design will now be presented. The computer simulation program based on solar still performance model from chapter two (and listed in the appendix B) was used to predict the productivity. Equation 4-2-1 from chapter four was used to estimate the cost of fresh water. The still under consideration is to be built near Los Angeles, California. It is double sloped glass covered type 1, with concrete side walls and sand insulation. The optimizing variables are: insulation thickness and side wall thickness. Good estimations of material and labor costs are necessary to obtain reliable results. In this work, ref. 9 and 10 have been used for pricing. All the data needed are shown below:

Place:	Los Angeles, California
Latitude:	34^o North
Soil:	$\alpha_s = 0.6 \cdot 10^{-6}\ m^2 / s$
	$k_s = 1.3\ W / m\text{-}K$
Still:	Type 1
Cover:	Glass 3 mm
	$k = 17\ m^{-1}$ (extinction coefficient)
Sides:	Concrete
	$k_{sid} = 1.5\ W / m\text{-}K$
	Price: $ 57.5 / m^3
	Thickness: varies from 3 to 8 cm

Insulation: Sand

$\alpha_{in} = 0.1\ m^2 / s$

Price: \$ 8.00 / m^3

Thickness: varies from 0. to 5.4 cm

Weather Data:

March: $T_a = 15.5^o\ C \pm 5^o\ C$

$Q_T = 18.70\ MJ / m^2$

June: $T_a = 21.1^o\ C \pm 7^o\ C$

$Q_T = 25.70\ MJ / m^2$

September: $T_a = 22.5^o\ C \pm 5^o\ C$

$Q_T = 21.50\ MJ / m^2$

December: $T_a = 15.5^o\ C \pm 4^o\ C$

$Q_T = 10.00\ MJ / m^2$

Wind velocity: 2. m / s

Rainfall: 200. l / year (average; collected)

$\pm$ 80. (winter, summer)

Economic Parameters:

I_o = \$ 25.00 / m^2

r = 10 %

n = 20 years

AP = 11.746 %

MR = 1.5 %

TI = 1.00 %

W = \$ 20.00 / h

L = 260. h / year

$$S = 0.0$$

$$A_w = 10\ 000\ m^2$$

Using the above data, 36 simulations have been carried out and the results are presented in tables 5-I, 5-II, 5-III and 5-IV. Each table is representative of the average performance in a specific season. Three different insulation thicknesses have been tested together with three side wall thicknesses. The first number in each box is the still efficiency (%), the second is the total daily distillate output without rainfall collection ($1 / m^2$) and the third is the cost of water (distillate + rain) per 1000 liters ($\$ / m^3$).

For this optimization study the only design quantities allowed to vary independently are the insulation and side wall thicknesses. The quantities that are dependent on them are: distillate output, Y_D , and capital investment, I . The latter one varies directly with insulation and side wall thicknesses. The value of $ 25.00 / m^2 was used for capital investment, I_o , of a standard still with 3 cm of side wall thickness and no base insulation. The value of $ 25.00 / m^2 rather than $ 31.25 / m^2 (from section 4 - 3) was used because of the size of proposed plant (10 000 m^2) while the estimated $ 31.25 was based on a 4600 m^2 solar still plant. For all the other cases with varying insulation and side wall thicknesses the incremental investment, ΔI , was calculated based on the cost of materials. For example: a still with X (m) side wall thickness will have an incremental investment of:

$$\Delta I = (X - 0.03) \cdot 1 \cdot 0.1 \cdot \text{cost of concrete per } m^3$$

where 0.03, 1, and 0.1 are standard values for the thickness, lenght and height of side walls respectively. Thus, the capital investment for that case is simply:

$$I = I_0 + \Delta I$$

The cost of materials (sand and concrete) used in this work already includes the cost of labor required for construction (ref. 9 and 10).

Distillate output is computed using the simulation program (SOLST) and rainfall collection is taken as 80 % of that from the annual rainfall maps.

Table 5-I. Efficiency, distillate output and fresh water cost for spring

MARCH INSULATION [M]

SIDE WALL [M]	0.000	0.027	0.054	
0.03	21.37	27.30	27.56	[%]
	1.72	2.20	4.10	[L/M2-DAY]
	4.93	4.10	4.10	[$/M3]
0.05	22.23	28.53	28.77	
	1.79	2.29	2.31	
	4.80	3.99	3.99	
0.08	23.08	29.76	30.00	
	1.86	2.39	2.41	
	4.69	3.87	3.87	

Table 5-II. Efficiency, distillate output and fresh water cost for summer

JUNE INSULATION [M]

SIDE WALL [M]	0.000	0.027	0.054	
0.03	26.61	33.27	33.49	[%]
	2.94	3.68	3.70	[L/M2-DAY]
	3.48	2.85	2.86	[$/M3]
0.05	27.66	34.69	34.91	
	3.06	3.83	3.86	
	3.37	2.76	2.76	
0.08	28.71	36.08	36.32	
	3.17	3.99	4.01	
	3.28	2.67	2.67	

Table 5-III. Efficiency, distillate output and fresh water cost for fall

SEPTEMBER		INSULATION [M]			
SIDE WALL [M]		0.000	0.027	0.054	
	0.03	26.68	32.91	33.17	[%]
		2.47	3.04	3.07	[L/M2-DAY]
		3.71	3.14	3.14	[$/M3]
	0.05	27.69	34.25	34.51	
		2.56	3.17	3.19	
		3.61	3.04	3.05	
	0.08	28.69	35.59	35.83	
		2.65	3.29	3.31	
		3.53	2.96	2.97	

Table 5-IV. Efficiency, distillate output and fresh water cost for winter

DECEMBER		INSULATION [M]			
SIDE WALL [M]		0.000	0.027	0.054	
	0.03	17.55	21.37	21.53	[%]
		0.75	0.92	0.93	[L/M2-DAY]
		7.11	6.47	6.48	[$/M3]
	0.05	18.08	22.19	22.34	
		0.78	0.95	0.96	
		7.01	6.38	6.40	
	0.08	18.62	22.98	23.16	
		0.80	0.99	1.00	
		6.96	6.28	6.29	

Two facts can be observed from the previous tables. First, the same still efficiency will result in unequal productivities in different seasons. That confirmes the previous conclusion (from chapter two) that productivity is dependent on the ambient temperature as well as on the insolation. Second, although the summer distillate output is four times the winter output, the fresh water cost is only slightly more than two times higher in the winter. This is because the rainfall for Los Angeles has winter maximum and summer minimum. Thus, the rainfalls helps to offset the cost and provides more continous fresh water supply.

Table 5-V shows the average yearly performance which is obtained by computing the mean value from tables 5-I through 5-IV.

Table 5-V. Average yearly efficiency, distillate output and water cost

YEARLY		INSULATION [M]			
SIDE WALL [M]		0.000	0.027	0.054	
	0.03	23.05	28.71	28.94	[%]
		1.97	2.46	2.48	[L/M2-DAY]
		4.81	4.14	4.15	[$/M3]
	0.05	23.92	29.92	30.13	
		2.05	2.56	2.58	
		4.70	4.04	4.05	
	0.08	24.78	31.10	31.33	
		2.12	2.67	2.68	
		4.62	3.94	3.95	

Several conclusions can be drawn from the results in table 5-V.

1. Efficiency and distillate output can be increased by 36 % (efficiency from 23.05 to 31.33 % and distillate output from 1.97 to 2.68 l/m^2) by a combination of increasing the side wall thickness by 5. cm and adding 5.4 cm of base insulation.

2. The cost of water produced can be decreased by 18 % (from $ 4.81 to $ 3.95 per 1000 liters) by increasing the side wall thickness by 5 cm and adding 2.7 cm of base insulation.

3. Sensitivity of distillate cost with respect to side wall thickness is small and almost linear (in the range studied). The cost is reduced by 4 % due to thicker side walls.

4. A thin layer of insulation (2.7 cm of sand) increase productivity and efficiency signifficantly (25 %) and decreases the cost of fresh water by 14 %. A thicker layer of sand insulation improves the performance and increases the cost of water very slightly.

Figures 5-1 and 5-2 show respectively the relationship between the cost of distillate output versus side thickness and versus insulation thickness. It can be concluded that optimal insulation for this case is approximately 25 - 30 mm of sand, while the side thickness should be just slightly thicker than the standard thickness of 3 cm. However, the selected side wall thickness should be based primarily on other design factors, since its influence on productivity and fresh water cost is small. Probably in the case of single sloped, type 2, solar still (with higher side wall) this factor would play a more significant role.

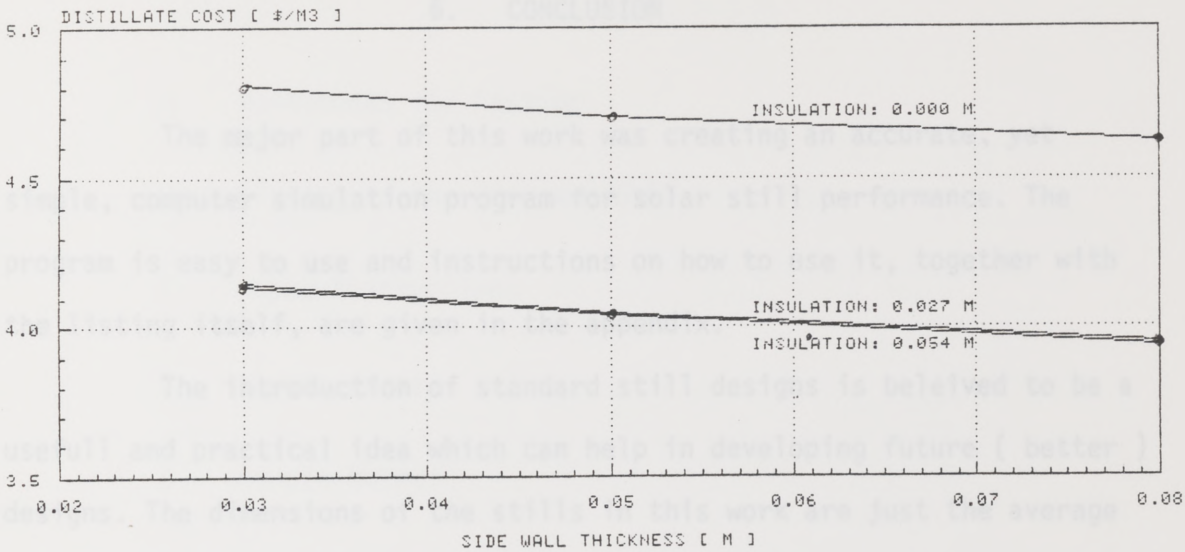

Figure 5-1. Fresh water cost versus side wall thickness.

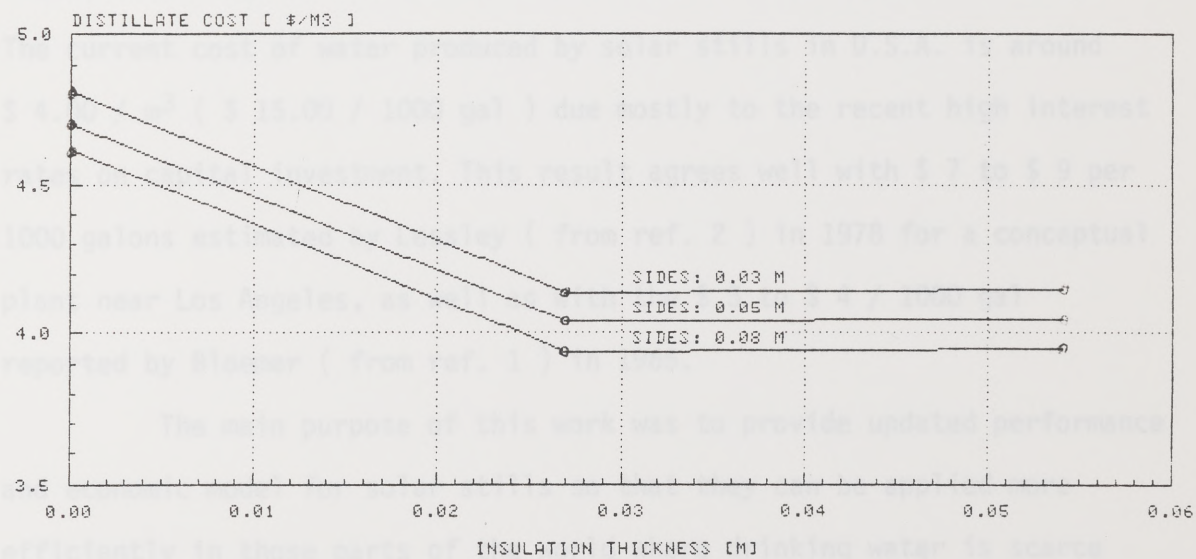

Figure 5-2. Fresh water cost versus insulation thickness.

6. CONCLUSION

The major part of this work was creating an accurate, yet simple, computer simulation program for solar still performance. The program is easy to use and instructions on how to use it, together with the listing itself, are given in the appendix.

The introduction of standard still designs is beleived to be a usefull and practical idea which can help in developing future (better) designs. The dimensions of the stills in this work are just the average of several well done commercial stills and they can be adjusted according to some standard manufacturing dimensions of glass, plastic concrete blocks etc.

The portion on economics of solar stills provides the most recent estimation of the cost of solar stills and of fresh water output. The current cost of water produced by solar stills in U.S.A. is around \$ 4.00 / m^3 (\$ 15.00 / 1000 gal) due mostly to the recent high interest rates on capital investment. This result agrees well with \$ 7 to \$ 9 per 1000 galons estimated by Lessley (from ref. 2) in 1978 for a conceptual plant near Los Angeles, as well as with the \$ 3 to \$ 4 / 1000 gal reported by Bloemer (from ref. 1) in 1965.

The main purpose of this work was to provide updated performance and economic model for solar stills so that they can be applied more efficiently in those parts of the world where drinking water is scarce and priceless, and where it will provide higher prosperity in less developed communities.

APPENDICES

APPENDIX A: Worksheets for Costing

Plant description

(a) Location:

Place ______________ Country ______________

Latitude ______________ Longitude ______________

Elevation ______________ m over sea level ______________

(b) Feed:

Type of water ______________

Salinity ______________ mg/L CaO

Total hardness ______________ meq/L CaO

Carbonate hardness ______________ meq/L CaO

Permanent hardness ______________ meq/L CaO

(c) Plant Area:

Water-evaporating surface ______________ m^2

Cover projected area ______________ m^2

Area inside boundary of the still ______________ m^2

(d) Available area for future enlargement ______________ m^2

(e) Number of distilling units:

Water-evaporating surface ______________ m^2 per unit

Cover projected area ______________ m^2 per unit

Depth of brine in basin ______________ mm

Cover material ______________

(f) Mean daily output per year ______________ $L/m^2 \cdot day$ or L/day

Maximum output ______________ $L/m^2 \cdot day$ or L/day

Construction of distillation units

(a) Basin structure per unit:

Gravel and sand ______	m^3 ×	______	=	______
Cement ______	kg ×	______	=	______
Concrete mix ______	m^3 ×	______	=	______
Precast concrete beams ______ (No. of dimensions)	pieces ×	______	=	______
Precast concrete posts ______ (No. of dimensions)	pieces ×	______	=	______
Steel for reinforcement ______	kg ×	______	=	______
Other materials ______	×	______	=	______

(b) Lining:

Butyl-rubber sheet ______	m^2 ×	______	=	______
Asphalt mats ______	m^2 ×	______	=	______
Polyethylene, sheet ______	m^2 ×	______	=	______
Others—specify ______	m^2 ×	______	=	______

(c) Sealing materials:

Silicone rubber ______	tubes ×	______	=	______
Asphalt cement ______	×	______	=	______

(d) Gutters and weirs:

Stainless-steel strip ______	m ×	______	=	______
Aluminum channel ______	m ×	______	=	______
Plastic channel ______	m ×	______	=	______
Asbestos—cement angles ______	m ×	______	=	______
Asbestos—cement strips ______	m ×	______	=	______
Other specify ______	m ×	______	=	______

(e) Insulation:

Polystyrene ______	m^2 ×	______	=	______
Other materials specify ______	×	______	=	______

(f) Labor for:

(1) Basin: concrete skilled ______	mh* ×	______	=	______
unskilled ______	mh ×	______	=	______
other work ______	mh ×	______	=	______
(2) Lining: skilled ______	mh ×	______	=	______
unskilled ______	mh ×	______	=	______
(3) Sealing: skilled ______	mh ×	______	=	______
unskilled ______	mh ×	______	=	______
(4) Gutters: skilled ______	mh ×	______	=	______
unskilled ______	mh ×	______	=	______
(5) Insulation: skilled ______	mh ×	______	=	______
unskilled ______	mh ×	______	=	______

(g) Any other (specify)

(h) Total cost of basin:

Cost ______ per m^2 evaporating surface

Cost ______ per m^2 of cover projected area

Cover construction

(a) Materials used:

Concrete curbs (dimensions) ______ pieces × ______ = ______

Aluminum angles (dimensions) ______ kg × ______ = ______

Aluminum T-ees (dimensions) ______ m × ______ = ______

Cover: Glass ______ m^2 × ______ = ______

Tedlar ______ m^2 × ______ = ______

Other plastics ______ m^2 × ______ = ______

Sealing materials:

Silicone rubber ______ tubes × ______ = ______

Silastic ______ tubes × ______ = ______

Other sealants ______ × ______ = ______

Primer ______ L × ______ = ______

(b) Labor for:

Cover structure— skilled ______ mh × ______ = ______

unskilled ______ mh × ______ = ______

Cover material— skilled ______ mh × ______ = ______

unskilled ______ mh × ______ = ______

(c) Total cost of cover:

Cost ______ per m^2 evaporating surface

Cost ______ per m^2 cover projected area

Cost of distillation units (total of 2 and 3)

(a) Basin ______

(b) Cover ______

Total of distillation units ______

Cost ______ per m^2 of evaporating surface

Cost ______ per m^2 of cover projected area

Site preparation

Minimum area required for projected output ______ m^2

Cost ______ m^2 × ______ = ______

Removal and relocation of:

(a) Earthen materials ______ m^2 × ______ = ______

(b) Rocky materials ______ m^2 × ______ = ______

Type of mechanical means used:

Machine hours ______ h × ______ = ______

Labor skilled ______ mh × ______ = ______

Labor unskilled ______ mh × ______ = ______

Any other special ______

Total cost of site preparation ______

Cost ______ per m^2 of evaporating surface

Cost ______ per m^2 of cover projected area

Piping and pumps

(a) Salt water:

_______ m pipe _______ mm ϕ × _______ = _______
_______ m pipe _______ mm ϕ × _______ = _______
_______ m pipe _______ mm ϕ × _______ = _______
_______ valves _______ mm ϕ × _______ = _______
_______ valves _______ mm ϕ × _______ = _______
_______ valves _______ mm ϕ × _______ = _______
_______ fittings _______ mm ϕ × _______ = _______
_______ fittings _______ mm ϕ × _______ = _______
_______ fittings _______ mm ϕ × _______ = _______

(b) Distillate:

_______ m pipe _______ mm ϕ × _______ = _______
_______ m pipe _______ mm ϕ × _______ = _______
_______ m pipe _______ mm ϕ × _______ = _______
_______ valves _______ mm ϕ × _______ = _______
_______ valves _______ mm ϕ × _______ = _______
_______ valves _______ mm ϕ × _______ = _______
_______ fittings _______ mm ϕ × _______ = _______
_______ fittings _______ mm ϕ × _______ = _______
_______ fittings _______ mm ϕ × _______ = _______

(c) Pumping (specify per pump):

_______ salt water pumps _______ mm ϕ × _______ = _______
_______ distillate pumps _______ mm ϕ × _______ = _______
_______ windmill pumps _______ mm ϕ × _______ = _______

(d) Total cost of piping and pumping:

Cost _______ per m^2 of evaporating surface
Cost _______ per m^2 cover projected area

Storage

Capacity for salt water _______ m^2
Capacity for distillate _______ m^2

(a) Materials used (specify by item) _______
(b) Labor: skilled _______ mh × _______ = _______
unskilled _______ mh × _______ = _______

(c) Total cost of storage:

Cost _______ per m^2 of storage capacity
Cost _______ per m^2 of evaporating surface
Cost _______ per m^2 of cover projected area

Fencing

Total area included inside fencing _______ m^2
(a) Materials used (specify by item) _______

(b) Labor: skilled _______ mh × _______ = _______
unskilled _______ mh × _______ = _______

(c) Total cost of fencing:

Cost _______ per m^2 of area included
Cost _______ per m^2 of evaporating surface
Cost _______ per m^2 of cover projected area

Other items of investment cost

(a) Facilities for pretreatment of salt water (specify by item) ______
(b) Facilities for post-treatment of distillate (specify by item) ______
(c) Transportation of materials to the site (specify by item) ______
(d) Engineering and design ______
(e) Supervision of construction ______
(f) Testing ______
(g) Brine disposal ______
(h) Power supply ______

Total ______

Total cost of other items

Cost ______ per m^2 of evaporating surface
Cost ______ per m^2 of cover projected area

Summary Cost of distillation units ______
Site preparation ______
Piping and pumps ______
Storage ______
Fencing ______

Other items ______

Total ______

Contingencies, 10 percent of total ______
Insurance ______
Interest during construction ______

Grand total ______

Cost ______ per m^2 of evaporating surface
Cost ______ per m^2 of cover projected area

APPENDIX B: Listing of the Program SOLST

```
      PROGRAM SOLST(INPUT,OUTPUT,TTY,TAPE5=INPUT,TAPE6=OUTPUT)
C     COPYRIGHT NINO ZAHRASTNIK 1982
C     UNIVERSITY OF TEXAS AT AUSTIN
C
C     INSTRUCTIONS FOR INPUT VARIABLES
C
C     1ST CARD: ALL REAL NUMBERS WITH MAXIMUM 4 DECIMAL PLACES
C               EACH DATUM OCCUPIES 10 SPACES. (FORMAT:5F10.4)
C                 QT - TOTAL DAYLY INSOLATION ON HORIZONTAL SURFACE
C                      IN MJ/M2
C                 XLATD - LATITUDE OF THE SITE IN DEGREES
C                     ( + FOR NORTH; - FOR SOUTH )
C                     (RANGE: -60. TO +60.)
C                 DAY - DAY OF THE YEAR. (RANGE: 0. TO 365.)
C                 VINT - INTERMITTIENCY. SIMULATES SCATTERED CLOUDS
C                      0. - CLEAR DAY
C                      0.5 - CLOUDY AFTERNOON
C                      1. TO 50. SMALL SCATTERED CLOUDS WHOLE DAY
C                FRDIR - FRACTION OF DIRECT TO TOTAL INSOLATION
C                        ( RANGE: 0. TO 1. )
C
C     2ND CARD: REAL NUMBERS ( FORMAT 3F10.4 )
C               TEMAX - MAXIMUM DAYLY TEMPERATURE [ KELVIN ]
C               TEMIN - MINIMUM DAYLY TEMPERATURE [ KELVIN ]
C               WV - WIND VELCCITY  [ M/S ]
C
C     3RD CARD: REAL NUMBERS ( FORMAT 5F10.4 )
C               AN - COVER INDEX OF REFRACTION
C                    ( EX. GLASS: 1.4 )
C               EXT - COVER EXTINCTION COEFFICIENT [ 1/M ]
C                    ( EX. GLASS: 17 M-1 )
C               DGL - COVER THICKNESS  [ M ]
C                    ( EX. GLASS: 0.003 ;  PLASTIC: 0.0005 )
C               EG - COVER EMISIVITY IN INFRARED REGION
C                    ( EX. GLASS: 0.95 )
C               PLTR - PLASTIC COVER TRANSMITTIVITY IN IR REGION
C                      PLTR = 1.- EG
C                      ( LEAVE BLANK FOR GLASS COVER )
C
C     4TH CARD: REAL NUMBERS ( FORMAT 5F10.4)
C               ACW - COVER TO WATER SURFACE AREA RATIO
C                     ( SOMEWHAT BIGER THAN 1.0 )
C               SL - SPECIFIC LENTH OF STILL [ M ]
C                    SL=CUBIC ROOT OF STILL TOTAL VOLUME
C               WD - WATER DEPTH IN STILL [ M ]
C                    ( TYPICALLY FROM 0.01 TO 0.1 )
C               ASW - SIDE WALLS TO WATER SURFACE AREA RATIO
C                     ( TYPICALLY FROM 0.1 TO 0.5 )
C               TYPE - TYPE OF STILL (EX. 1. 2. 3. ETC )
C                      ( USED ONLY TO KEEP BETTER RECORDS )
C
C     5TH CARD: REAL NUMBERS (FORMAT 2F10.4)
C               CW - HEAT CAPACITY OF SALINE WATER [ J/KG-K ]
C                    USUALLY AROUND 4800.
C               ROW - DENSITY OF SALINE WATER [ KG/M3 ]
C                    USUALLY AROUND 1000.
C
C     6TH CARD: REAL NUMBERS ( FORMAT 4F10.4 )
```

```
C             XKIN - CONDUCTANCE OF INSULATION MATERIAL [ W/M-K ]
C             THIN - INSULATION THICKNESS [ M ]
C                  ( 0.0 - NO INSULATION )
C             XKSID - CONDUCTANCE OF SIDE WALLS [ W/M-K ]
C             THSID - SIDE WALL THICKNESS [ M ]
C
C     7TH CARD: REAL NUMBERS WITH 8 DECIMAL PLACES (FORMAT 3F10.8)
C             ASOIL - THERMAL DIFFUSIVITY OF SOIL [ M2/S ]
C             XKSOIL - CONDUCTANCE OF SOIL [ W/M-K ]
C             AIN - THERMAL DIFFUSIVITY OF INSULATION [ M2/S ]
C
C     8TH CARD: CHARACTERS INPUT: 10 LETTERS PER NAME MAXIMUM
C             ( FORMAT 2A10 )
C             PLACE - NAME OF THE PLACE
C             COUNTR - NAME OF THE COUNTRY
C
C     9TH CARD: CHARACTERS INPUT: 10 LETTERS PER NAME MAXIMUM
C             ( FORMAT 3A10 )
C             COV - NAME OF THE COVER MATERIAL
C             SIDES - NAME OF THE SIDE WALLS MATERIAL
C             INSU - NAME OF THE INSULATION MATERIAL
C
C     ***********************************************************
C
C     **** DIMENSION 18 TEMPERATURES OF THE SOIL UNDER THE STILL ****
      DIMENSION T(18),T1(18),TIN(50),TIN1(50)
1     FORMAT(6F10.4)
2     FORMAT(10F10.2)
3     FORMAT(4F10.8)
4     FORMAT(7X,3HTIM,6X,4HEFFI,7X,3HDTW,6X,4HDSTL)
5     FORMAT(6X,4HISOL,5X,5HQABSC,5X,5HQTRSC,7X,3HQRC,6X,4HQCVC,
     *8X,2HQR,7X,3HQCV,8X,2HQE,8X,2HQB,6X,4HQSID)
6     FORMAT(6X,4HTAMB,8X,2HTC,6X,4HTSID,8X,2HTW,6X,4HT(1),6X,
     *4HT(3),6X,4HT(6),6X,4HT(9),5X,5HT(12),5X,5HT(15))
7     FORMAT(3A10)
8     FORMAT(7HPLACE :,15X,A10,4X,15HTYPE OF STILL :,F2.0)
9     FORMAT(9HCOUNTRY :,12X,A10,5X,7HCOVER :,A10)
10    FORMAT(10HLATITUDE :,11X,F6.2,9X,12HINSULATION :,A10,1X,
     *F8.3,1X,2H M)
11    FORMAT(6H DAY :,15X,F5.0,10X,7HSIDES :,A10,1X,F8.3,1X,2H M)
12    FORMAT(18HTOTAL INSOLATION :,3X,F6.2,3H MJ,6X,14HPRODUCTIVITY :,
     *F5.2,1X,5HL/DAY)
13    FORMAT(22H AMBIENT TEMPERATURE :,F6.2,2H C,6X,12HEFFICIENCY :,
     *F5.2,1X,1H%)
14    FORMAT(13HWIND VELOCITY,8X,F6.2,1X,3HM/S)
15    FORMAT(17HPERCENT DIFFUSE :,4X,F6.2)
16    FORMAT(15HINTERMITIENCY :,6X,F6.2)
C     ************** READ IN THE DATA ***************************
      READ(5,1)QT,XLATO,DAY,VINT,FRDIR
      READ(5,1)TEMAX,TEMIN,WV
      READ(5,1)AN,EXT,DGL,EG,PLTR
      READ(5,1)ACW,SL,WD,ASW,TYPE
      READ(5,1)CW,ROW
      READ(5,1)XKIN,THIN,XKSID,THSID
      READ(5,3)ASOIL,XKSOIL,AIN
      READ(5,7)PLACE,COUNTR
      READ(5,7)COV,SIDES,INSU
      DATA JJ/'GLASS      '/
      TMEAN=(TEMAX+TEMIN)/2.-273.
      DIFF=(1.-FRDIR)*100.
      DX=SQRT(1800.*ASOIL)
```

```
      DXIN=SQRT(1800.*AIN)
      NIN=IFIX(THIN/DXIN)+1
      IF (THIN.NE.0.)THIN=(NIN-1)*DXIN
C     ************ ASTRONOMIC PARAMETERS **************
      DEC=.40928*SIN((284.+DAY)/58.09)
      XLAT=XLATD/57.3
      DLEN=7.64*ACOS(-TAN(XLAT)*TAN(DEC))-1.
      SR=12.-DLEN/2.
      SS=12.+DLEN/2.
C     ****************************************************************
C     ******************* BEGINING OF THE PROGRAM ****************
C     *** FIRST LOOP (II=1) ONLY ESTABLISHES SOIL TEMPERATURES ***
      DO 500 II=1,2
      DSTL=SISOL=EF=PAR=0.
      TIM=IFIX(SR)
      KTT=IFIX(24./0.25)
C     **************** BEGINING OF THE 24 HOUR LOOP ****************
      DO 100 KT=1,KTT+1
      DTC1=DTC2=XI=1.
      IPR=0
      IF(TIM.GE.SS.OR.TIM.LE.SR)XI=XIDIR=XIDIF=0.
      IF((XI).EQ.0.) GOTO 120
      IF(VINT.GE.0.5)GOTO 110
      XIDIR=GT*436.33/DLEN*SIN((TIM-SR)/DLEN*3.1416)*FRDIR
      XIDIF=(1.-FRDIR)*XIDIR/FRDIR
      XI=XIDIR+XIDIF
      GOTO 120
110   XIDIR=FRDIR*QT*436.33/DLEN*SIN((TIM-SR)/DLEN*3.1416)*
     *(1.+COS((TIM-SR)/DLEN*VINT*6.283))
      XI=QT*436.33/DLEN*SIN((TIM-SR)/DLEN*3.1416)
      XIDIF=(1.-FRDIR)*XI
      XI=XIDIR+XIDIF
      XIMAX=1100.*SIN((TIM-SR)/DLEN*3.1416)
      IF(XI.GT.XIMAX) XI=XIMAX
      XIDIR=XI*FRDIR
      XIDIF=XI*(1.-FRDIR)
120   IF(TIM.GT.24.) TIM=TIM-24.
      ICOV=0
C     **************** OUTSIDE TEMPERATURE ******************
      TAMB=(TEMAX+TEMIN)/2.+(TEMAX-TEMIN)/2.*COS(.2618*(TIM-(SS+12)/2))
      TSKY=.0552*SQRT(TAMB**3)
      IF(PAR.EQ.1)GOTO 125
      IF(II.NE.1) GOTO 60
      TC=TW=TSID=TAMB
      DO 40 J=1,NIN
40    TIN(J)=TAMB
      DO 50 J=1,17
50    T(J)=TAMB
      T(18)=(TEMAX+TEMIN)/2.
60    PAR=1
125   IF(TIM.LE.SR.OR.TIM.GE.SS)GOTO 195
C     ****************** ENERGY BALANCE ON THE COVER ****************
      OMEGA=(TIM-12.)/3.82
      CTHET=SIN(DEC)*SIN(XLAT)+COS(DEC)*COS(XLAT)*COS(OMEGA)
      THET=ACOS(CTHET)
130   THET2=ASIN(SIN(THET)/AN)
      TAUA=EXP(-EXT*DGL/COS(THET2))
      R1=(SIN(THET2-THET))**2/(SIN(THET2+THET))**2
      R2=(TAN(THET2-THET))**2/(TAN(THET2+THET))**2
      TAU=TAUA/2.*((1.-R2)/(1.+R2)+(1.-R1)/(1.+R1))
      ALFA=1.-TAUA
      RE=1.-TAU-ALFA
```

```
      IF(ICOV.EQ.1)GOTO 140
      REDR=RE
      TAUDR=TAU
      ALFADR=ALFA
      THET=1.012
      ICOV=1
      GOTO 130
140   TAUDF=TAU
      ALFADF=ALFA
      REDF=RE
      ABSIC=(XIDIR*ALFADR+XIDIF*ALFADF)*ACW
      TRSIC=(XIDIR*TAUDR+XIDIF*TAUDF)*ACW
      GOTO 190
195   ABSIC=TRSIC=0.
 190  QRC=5.67E-8*EG*(TC**4-TSKY**4)*ACW
      QCVC=8.6*EXP(.6*ALOG(WV)-.4*ALOG(SL))*(TC-TAMB)*ACW
      QO=QRC+QCVC
C     ************* HEAT BALANCE FOR THE BRINE ****************
      IF (COV.EQ.JJ) PLTR=0.
      QR=5.1E-8*(TW**4-TC**4)*(1.-PLTR)
      QROUT=PLTR*5.1E-8*(TW**4-TSKY**4)
      TP=TW
      IF(IPR.EQ.1) TP=TC
180   TX=647.27-TP
      PR=3206.18*10**(-((TX/TP*(3.2438+5.86826E-3*TX
     *+1.17E-8*TX**3)/(1.+2.1878E-3*TX))))
      IF(IPR.EQ.1) GOTO 175
      PRW=PR
      IPR=1
      TP=TC
      GOTO 180
175   PRG=PR
      QCV=.884*(TW-TC+(PRW-PRG)/(39.-PRW)*TW)**(1./3.)*(TW-TC)
      HFG=1359.2-1.035*TW
      IF((TW-TC).EQ.0) GOTO 160
      QE=.11*QCV*HFG*(PRW-PRG)/(TW-TC)
      GOTO 165
160   QE=0.
165   QL=(QE+QCV)*0.05
      QI=QR+QE+QCV-QL
      GOTO 215
200   TC=TC-DTC2
      DTC1=DTC2/2.
      GOTO 190
220   TC=TC+DTC1
      DTC2=DTC1/2.
      GOTO 190
215   IF((ABSIC+QI-QO).LT.(-5.)) GOTO 200
      IF((ABSIC+QI-QO).GT.5.) GOTO 220
      HWOI=QE*CW*(TW+TC-2.*TAMB)/2400000.
      WABS=.95*TRSIC
      IF(NIN.GT.2) QB=XKIN/DXIN*(TW-TIN(2))
      IF(NIN.EQ.1) QB=XKSOIL/DX*(TW-T(2))
      IF(NIN.EQ.2) QB=XKIN/THIN*(TW-T(1))
      TSID=(TW*XKSID/THSID+TAMB*30.)/(30.+XKSID/THSID)
      QSID=30.*(TSID-TAMB)*ASW
      DTW=(WABS-HWOI-QSID-QB-QR-QROUT-QCV-QE)*0.25*3600./CW/ROW/WD
      IF(NIN.EQ.1) T(1)=TW
      TIN(1)=TW
      IF(NIN.EQ.2) GOTO 280
      IF(NIN.LT.3) GOTO 290
C     *************** TRANSIENT INSULATION TEMPERATURES ***************
```

```
      DC 250 J=2,(NIN-1)
 250  TIN1(J)=(TIN(J-1)+TIN(J+1))/2.
      DO 251 J=2,(NIN-1)
 251  TIN(J)=TIN1(J)
C
C     **************** TRANSIENT SOIL TEMPERATURES ******************
 280  T(1)=TIN(NIN)=(TIN(NIN-1)+T(2))/2.
      IF(NIN.EQ.2)TIN(2)=T(1)
 290  DC 300 J=2,17
 300  T1(J)=(T(J-1)+T(J+1))/2.
      DO 301 J=2,17
 301  T(J)=T1(J)
C
C     ******************* CUMULATIVE DISTILLATE OUTPUT ****************
      DSTL=DSTL+QE/HFG*1.47*0.25
      IF(XI.LE.0) GOTO 80
      SISOL=SISOL+XI*.25
      EF=64611.*DSTL/SISCL
C
C     *************** PRINT OUTPUT EACH FULL HCUR *********************
 80   IF(XI.LE.0.)EF=0.
      IF(II.EQ.1)GOTO 90
      IF((IFIX(TIM)-TIM).NE.0.) GCTO 90
      WRITE(6,*)
      WRITE(6,4)
      WRITE(6,2)TIM,EF,DTW,DSTL
      WRITE(6,5)
      WRITE(6,2) XI,ABSIC,TRSIC,QRC,QCVC,QR,QCV,QE,QB,QSID
      WRITE(6,6)
      WRITE(6,2) TAMB,TC,TSID,TW,T(1),T(3),T(6),T(9),T(12),T(15)
  90  TIM=TIM+0.25
 100  TW=TW+DTW
 500  CONTINUE
      EFF=232.6*DSTL/QT
      WRITE(6,*)
      WRITE(6,*)
      WRITE(6,8)PLACE,TYPE
      WRITE(6,9)COUNTR,COV
      WRITE(6,10)XLATO,INSU,THIN
      WRITE(6,11)DAY,SIDES,THSID
      WRITE(6,12)QT,DSTL
      WRITE(6,13)TMEAN,EFF
      WRITE(6,14)WV
      WRITE(6,15)DIFF
      WRITE(6,16)VINT
      END
```

APPENDIX C: Input Instructions for SOLST

```
PROGRAM SOLST(INPUT,OUTPUT,TTY,TAPE5=INPUT,TAPE6=OUTPUT)
COPYRIGHT NINO ZAHRASTNIK 1982
UNIVERSITY OF TEXAS AT AUSTIN

INSTRUCTIONS FOR INPUT VARIABLES

1ST CARD:  ALL REAL NUMBERS WITH MAXIMUM 4 DECIMAL PLACES
           EACH DATUM OCCUPIES 10 SPACES. (FORMAT:5F10.4)
           QT - TOTAL DAYLY INSOLATION ON HORIZONTAL SURFACE
                IN MJ/M2
           XLATD - LATITUDE OF THE SITE IN DEGREES
                ( + FOR NORTH; - FOR SOUTH )
                (RANGE: -60. TO +60.)
           DAY - DAY OF THE YEAR. (RANGE: 0. TO 365.)
           VINT - INTERMITTIENCY. SIMULATES SCATTERED CLOUDS
                0. - CLEAR DAY
                0.5 - CLOUDY AFTERNOON
                1. TO 50. SMALL SCATTERED CLOUDS WHOLE DAY
           FRDIR - FRACTION OF DIRECT TO TOTAL INSOLATION
                ( RANGE: 0. TO 1. )

2ND CARD: REAL NUMBERS ( FORMAT 3F10.4 )
          TEMAX - MAXIMUM DAYLY TEMPERATURE [ KELVIN ]
          TEMIN - MINIMUM DAYLY TEMPERATURE [ KELVIN ]
          WV - WIND VELOCITY [ M/S ]

3RD CARD: REAL NUMBERS ( FORMAT 5F10.4 )
          AN - COVER INDEX OF REFRACTION
                ( EX. GLASS: 1.4 )
          EXT - COVER EXTINCTION COEFFICIENT [ 1/M ]
                ( EX. GLASS: 17 M-1 )
          DGL - COVER THICKNESS [ M ]
                ( EX. GLASS: 0.003 ;  PLASTIC: 0.0005 )
          EG - COVER EMISIVITY IN INFRARED REGION
                ( EX. GLASS: 0.95 )
          PLTR - PLASTIC COVER TRANSMITTIVITY IN IR REGION
                 PLTR = 1.- EG
                ( LEAVE BLANK FOR GLASS COVER )
```

```
4TH CARD: REAL NUMBERS ( FORMAT 5F10.4)
          ACW - COVER TO WATER SURFACE AREA RATIO
                ( SOMEWHAT BIGER THAN 1.0 )
          SL - SPECIFIC LENTH OF STILL [ M ]
               SL=CUBIC ROOT OF STILL TOTAL VOLUME
          WD - WATER DEPTH IN STILL [ M ]
               ( TYPICALLY FROM 0.01 TO 0.1 )
          ASW - SIDE WALLS TO WATER SURFACE AREA RATIO
                ( TYPICALLY FROM 0.1 TO 0.5 )
          TYPE - TYPE OF STILL (EX. 1. 2. 3. ETC )
                 ( USED ONLY TO KEEP BETTER RECORDS )

5TH CARD: REAL NUMBERS (FORMAT 2F10.4)
          CW - HEAT CAPACITY OF SALINE WATER [ J/KG-K ]
               USUALLY AROUND 4800.
          ROW - DENSITY OF SALINE WATER [ KG/M3 ]
                USUALLY AROUND 1000.

6TH CARD: REAL NUMBERS ( FORMAT 4F10.4 )
          XKIN - CONDUCTANCE OF INSULATION MATERIAL [ W/M-K ]
          THIN - INSULATION THICKNESS [ M ]
                 ( 0.0 - NO INSULATION )

          XKSID - CONDUCTANCE OF SIDE WALLS [ W/M-K ]
          THSID - SIDE WALL THICKNESS [ M ]

7TH CARD: REAL NUMBERS WITH 8 DECIMAL PLACES (FORMAT 3F10.8)
          ASOIL - THERMAL DIFFUSIVITY OF SOIL [ M2/S ]
          XKSOIL - CONDUCTANCE OF SOIL [ W/M-K ]
          AIN - THERMAL DIFFUSIVITY OF INSULATION [ M2/S ]

8TH CARD: CHARACTERS INPUT: 10 LETTERS PER NAME MAXIMUM
          ( FORMAT 2A10 )
          PLACE - NAME OF THE PLACE
          COUNTR - NAME OF THE COUNTRY

9TH CARD: CHARACTERS INPUT: 10 LETTERS PER NAME MAXIMUM
          ( FORMAT 3A10 )
          COV - NAME OF THE COVER MATERIAL
          SIDES - NAME OF THE SIDE WALLS MATERIAL
          INSU - NAME OF THE INSULATION MATERIAL
```

APPENDIX D: Sample Input

```
18.7        34.00       74.0        0.00        0.80
293.5       283.5       2.
1.4         17.1        0.003       0.94
1.012       1.89        0.03        0.15        1.
4180.       1000.
0.50        0.06        1.5         0.03
.0000006    1.3         .0000004
L.ANGELES   U.S.A.
GLASS       CONCRETE    SAND
```

APPENDIX E: Sample Output

TIM	EFFI	DTW	DSTL						
6.00	0	-.04	.00						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
0	0	0	68.90	-38.35	17.37	5.28	7.48	-24.62	-.03
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
285.27	281.52	285.26	285.26	287.67	289.66	291.16	291.06	290.23	289.31
TIM	EFFI	DTW	DSTL						
7.00	26.45	.30	.01						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
82.77	5.70	45.40	66.24	-41.90	14.01	3.95	5.72	-19.84	-3.07
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
286.36	282.27	285.68	285.27	287.40	289.25	290.81	290.89	290.21	289.33
TIM	EFFI	DTW	DSTL						
8.00	5.08	1.28	.02						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
296.73	19.58	228.90	72.51	-26.48	14.25	3.90	6.60	13.67	1.07
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
287.61	285.02	287.84	287.99	288.17	289.07	290.48	290.72	290.17	289.34
TIM	EFFI	DTW	DSTL						
9.00	3.70	1.87	.04						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
485.51	30.39	412.65	83.82	-1.47	27.09	8.69	19.32	61.63	14.68
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
288.91	288.77	292.17	294.13	290.85	289.62	290.23	290.54	290.11	289.34
TIM	EFFI	DTW	DSTL						
10.00	4.55	2.03	.09						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
633.11	37.82	554.88	104.04	39.17	43.00	15.00	47.13	104.51	33.17
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
290.15	294.02	297.56	301.98	294.98	291.08	290.18	290.38	290.04	289.32
TIM	EFFI	DTW	DSTL						
11.00	6.47	1.76	.19						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
726.99	42.11	643.72	127.81	83.54	59.43	21.68	95.06	133.66	51.94
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
291.35	299.52	302.89	309.81	299.76	293.30	290.44	290.26	289.95	289.30
TIM	EFFI	DTW	DSTL						
12.00	9.03	1.27	.38						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
759.19	43.51	673.92	152.91	127.34	69.73	25.58	147.52	144.16	67.13
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
292.31	304.77	307.23	316.18	304.31	295.93	291.05	290.24	289.88	289.26
TIM	EFFI	DTW	DSTL						
13.00	11.83	.63	.63						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
726.98	42.11	643.72	170.09	155.90	76.11	27.96	191.56	137.61	76.67
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
293.02	308.27	310.06	320.28	307.97	298.58	291.96	290.34	289.83	289.23
TIM	EFFI	DTW	DSTL						
14.00	14.52	-.02	.92						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
633.10	37.82	554.88	176.24	165.88	78.14	28.68	209.54	117.53	79.84
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
293.42	309.64	311.16	321.81	310.34	300.89	293.08	290.59	289.81	289.20
TIM	EFFI	DTW	DSTL						
15.00	16.89	-.65	1.22						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
485.51	30.39	412.65	169.45	155.00	77.21	28.42	198.54	86.80	76.77
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
293.46	308.64	310.54	320.78	311.23	302.61	294.26	290.97	289.85	289.18

TIM	EFFI	DTW	DSTL						
16.00	18.92	-1.22	1.47						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
296.73	19.58	228.90	150.96	124.59	73.11	27.07	162.43	47.52	67.66
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
293.21	305.39	308.24	317.26	310.54	303.56	295.38	291.46	289.96	289.18

TIM	EFFI	DTW	DSTL						
17.00	20.69	-1.61	1.66						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
82.77	5.70	45.40	124.84	79.56	65.58	24.45	114.37	3.90	53.43
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
292.61	300.39	304.48	311.61	308.34	303.64	296.31	291.99	290.12	289.20

TIM	EFFI	DTW	DSTL						
18.00	0	-1.18	1.79						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
0	0	0	103.32	39.95	54.91	20.26	72.72	-23.90	38.85
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
291.73	295.64	300.37	305.55	305.22	302.87	296.97	292.53	290.33	289.25

TIM	EFFI	DTW	DSTL						
19.00	0	-.82	1.87						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
0	0	0	93.75	20.49	46.70	16.92	50.58	-30.84	30.21
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
290.64	292.64	297.35	301.38	302.47	301.67	297.28	293.02	290.58	289.32

TIM	EFFI	DTW	DSTL						
20.00	0	-.65	1.93						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
0	0	0	88.07	7.63	42.72	15.46	40.04	-33.84	25.21
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
289.39	290.14	295.00	298.36	300.22	300.41	297.30	293.42	290.85	289.42

TIM	EFFI	DTW	DSTL						
21.00	0	-.53	1.98						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
0	0	0	85.50	.51	39.76	14.39	33.15	-35.67	22.14
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
288.09	288.14	293.01	295.96	298.32	299.19	297.13	293.71	291.10	289.53

TIM	EFFI	DTW	DSTL						
22.00	0	-.47	2.02						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
0	0	0	82.81	-6.89	38.82	14.26	29.45	-37.42	20.03
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
286.81	286.14	291.27	293.94	296.67	298.03	296.82	293.88	291.33	289.65

TIM	EFFI	DTW	DSTL						
23.00	0	-.41	2.06						
ISOL	QABSC	QTRSC	QRC	QCVC	GR	QCV	QE	QB	QSID
0	0	0	81.99	-10.36	36.95	13.61	25.70	-38.40	18.38
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
285.65	284.64	289.74	292.19	295.19	296.94	296.44	293.97	291.52	289.77

TIM	EFFI	DTW	DSTL						
24.00	0	-.35	2.09						
ISOL	QABSC	QTRSC	QRC	QCVC	GR	QCV	QE	QB	QSID
0	0	0	81.29	-13.25	35.15	12.94	22.62	-38.89	16.84
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
284.69	283.39	288.43	290.68	293.86	295.91	296.00	293.97	291.68	289.88

TIM	EFFI	DTW	DSTL						
1.00	0	-.30	2.12						
ISOL	QABSC	QTRSC	QRC	QCVC	QR	QCV	QE	QB	QSID
0	0	0	80.35	-16.25	33.23	12.17	19.93	-39.12	15.14
TAMB	TC	TSID	TW	T(1)	T(3)	T(6)	T(9)	T(12)	T(15)
286.81	286.14	291.27	293.94	296.67	298.03	296.82	293.88	291.33	289.65

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     TIM       EFFI        DTW       DSTL
    2.00          0       -.25       2.15
    ISCL      QABSC      QTRSC        QRC       QCVC         QR        QCV         QE         QB       QSID
       0          0          0      78.93     -19.84      31.16      11.30      17.53     -38.82      13.11
    TAMB         TC       TSID         TW       T(1)       T(3)       T(6)       T(9)      T(12)      T(15)
  283.58     281.64     286.49     288.24     291.62     294.06     295.04     293.79     291.85     290.04

     TIM       EFFI        DTW       DSTL
    3.00          0       -.20       2.17
    ISCL      QABSC      QTRSC        QRC       QCVC         QR        QCV         QE         QB       QSID
       0          0          0      76.88     -24.30      29.06      10.38      15.47     -37.34      10.76
    TAMB         TC       TSID         TW       T(1)       T(3)       T(6)       T(9)      T(12)      T(15)
  283.52     281.14     285.91     287.34     290.70     293.23     294.55     293.64     291.88     290.10

     TIM       EFFI        DTW       DSTL
    4.00          0       -.14       2.19
    ISCL      QABSC      QTRSC        QRC       QCVC         QR        QCV         QE         QB       QSID
       0          0          0      75.36     -27.12      25.63       8.82      12.87     -35.56       7.98
    TAMB         TC       TSID         TW       T(1)       T(3)       T(6)       T(9)      T(12)      T(15)
  283.75     281.14     285.57     286.63     289.92     292.48     294.05     293.45     291.87     290.14

     TIM       EFFI        DTW       DSTL
    5.00          0       -.10       2.20
    ISCL      QABSC      QTRSC        QRC       QCVC         QR        QCV         QE         QB       QSID
       0          0          0      72.04     -33.22      23.23       7.76      11.16     -33.18       4.90
    TAMB         TC       TSID         TW       T(1)       T(3)       T(6)       T(9)      T(12)      T(15)
  284.39     281.14     285.48     286.13     289.28     291.81     293.57     293.23     291.84     290.16

     TIM       EFFI        DTW       DSTL
    6.00          0       -.02       2.22
    ISCL      QABSC      QTRSC        QRC       QCVC         QR        QCV         QE         QB       QSID
       0          0          0      70.71     -34.51      18.31       5.63       8.20     -30.33       1.54
    TAMB         TC       TSID         TW       T(1)       T(3)       T(6)       T(9)      T(12)      T(15)
  285.27     281.89     285.61     285.81     288.77     291.22     293.10     293.00     291.77     290.16

PLACE :                 L.ANGELES     TYPE OF STILL :1.
COUNTRY :             U.S.A.          COVER :GLASS
LATITUDE :              34.00         INSULATION :SAND             .054  M
 DAY :                   74.          SIDES :CONCRETE        .030  M
TOTAL INSOLATION :  18.70 MJ          PRODUCTIVITY : 2.22 L/DAY
 AMBIENT TEMPERATURE : 15.50 C        EFFICIENCY :27.56 %
WIND VELOCITY            2.00 M/S
PERCENT DIFFUSE :     20.00
INTERMITIENCY :             0
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APPENDIX F: Nomenclature for SOLST Output

DSTL - cummulative distillate (l/m^2)

DTW - brine temperature change for 15 min. time interval (K)

EFFI - instantenious still efficiency (%)

ISOL - instantenious global insolation (W/m^2)

QABSC - heat absorbed in the cover (W/m^2)

QB - base heat flow (W/m^2)

QCV - convection between brine and cover (W/m^2)

QCVC - convection losses from cover to surroundings (W/m^2)

QE - evaporation from brine to cover (W/m^2)

QR - radiation between brine and cover (W/m^2)

QRC - radiation losses from cover to surroundings (W/m^2)

QSID - side heat losses (W/m^2)

QTRSC - solar radiation transmitted through cover (W/m^2)

T(1) through T(15) - transient soil element temperatures (K)

TAMB - ambient temperature (K)

TC - cover temperature (K)

TIM - 24 hour time of day (h)

TSID - side wall temperature on the outside surface (K)

TW - brine temperature (K)

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